INTERNATIONAL
HELLENIC
UNIVERSITY

Modelling of Energy Production from Alternative Fuels

Christina Andreadou

SID: 3302140003

SCHOOL OF SCIENCE & TECHNOLOGY

A thesis submitted for the degree of

Master of Science (MSc) in Energy Systems

NOVEMBER 2015

THESSALONIKI – GREECE

INTERNATIONAL HELLENIC UNIVERSITY

Modelling of Energy Production from alternative fuels

Christina Andreadou

SID: 3302140003

Supervisor: Dr G. Martinopoulos

Supervising Committee Members: Dr. HeracleousAssist.

Dr. Sardi

SCHOOL OF SCIENCE & TECHNOLOGY

A thesis submitted for the degree of

Master of Science (MSc) in Energy Systems

NOVEMBER 2015

THESSALONIKI – GREECE

Acknowledgement

This dissertation would not have been possible without the guidance and support of several individuals who in one way or another contributed and provided their valuable assistance in the preparation and completion of this work.

First and foremost, my ultimate gratitude to my supervisor, Dr. Georgios Martinopoulos, academic associate at the International Hellenic University, who offered me the opportunity to work on this theme and whose inspirational guidance, great patience and constant encouragement supported me through the whole process and propelled me to complete this work.

A lot of my gratitude goes to Dr. Eleni Heracleous, Assistant Professor at the International Hellenic University, for the significant guidance and cheerful encouragement for the specific accomplishment.

Abstract

This dissertation was written as a part of the MSc in Energy Systems at the International Hellenic University.

The constant increase of Municipal Solid Waste (MSW) as a result of the population increase, urbanisation as well as human development is a severe global issue threatening human health, environmental sustainability. The uncontrolled deposition of MSW in landfills without specific treatment is a serious pollution source. Although many European countries have already conformed to the Waste Framework Directive of the EU Parliament, which order an integrated municipal waste treatment including Waste-to-Energy (WtE) facilities for energy recovery, Greece still faces the uncontrolled solid waste deposition without pre-treatment and energy recovery operations.

The aims of this thesis work are to study the modelling of a Fluidized Bed Combustion Boiler CHP plant for energy production from MSW of Thessaloniki, Greece, by using the COCO simulation software. Three cases with three different pressure types of fluidized boilers have been examined. The boilers pressures that have been studied are 2MPa, 5MPa and 10MPa. Apart from the boiler, each potential CHP plant consists of a high and a low pressure turbine, a condenser and a low pressure pump. Simulation models for these different cases have been developed and validated against available experimental data.

In the first chapter of this work, an introduction takes place, concerning the main reasons of the growth rate of Municipal Solid Waste production through years as well as its environmental footprint and impacts on human health. Additionally, this chapter includes the effectiveness of WtE plants of many countries in the world, not only in waste reduction but in energy production as well. In the second chapter, a presentation of the integrated waste treatment was developed, in conjunction with the differences between the Greek and European waste management methods and facilities. In the third and fourth chapter a detailed presentation of biomass conversion to energy technologies and COCO Simulator software was manifested, respectively. Whilst, in the fifth chapter, the parts and operation of a common FBB Biomass Combined Heat

and Power Generation (CHP) facility was presented. In the final part of this thesis, three cases for the simulation of a FBB CHP plant for energy production from MSW in Thessaloniki through COCO were analytically developed. The COCO results indicated that the first case covers the total energy needs of 13.73% of the city's households, the second serves the 14.9%, while the third the 15.43%.

Contents

1. Introduction

Energy supports human life and it has great significance for the preservation of human's evolution. Energy is a convertible technological currency on which societies depend and without which the whole system of society would collapsed. During the evolutionary process of humanity, the upward trend of energy demand was obvious. This demand still experiences and it will continue to meet major increase in the near future. For centuries, fossil fuels such as oil, coal and natural gas, constitute the main source of energy and the driving force for evolution. However, the fact that these sources are not regenerated in short period of time in conjunction with the constant raise of their consumption result in their rapid depletion. Despite of their exhaustion, fossil fuels are also origins for climatic changes, greenhouse gas emissions, the global warming of the planet, pollution of the environment and degradation of human health. In order to struggle this situation, human turned to the RES (Renewable Energy Sources). RES are renewable and abundant in nature and their use is considered to contribute to the sustainable development in a variety of aspects (environmental, economic and social). The objective is to succeed the substitution of fossil fuels by RES as alternative and sustainable fuels. The last decades, solar energy, wind power, hydro power, geothermal energy and bioenergy meet great development. Although to most people solar and wind energy sound more popular, biomass is the most renewable, sustainable and efficient in energy production source. Biomass, a term which introduced for the first time from Eugene Adam and referred as the quantity of every living organism from the five kingdoms in biology sector: plants, fungi, protists (unicellular organisms like fees and micro-algae) and monerans (cells without core like bacteria and blue-green algae), describe, today, all organic matter produced by photosynthesis, existing on the earth's surface. It includes all water- and land-based vegetation and trees, and all waste biomass such as Municipal Solid Waste (MSW), municipal biosolids (sewage), and animal wastes, forestry and agricultural residues, and certain types of industrial wastes [1][2][3][4]. Efforts to produce energy from second generation biofuels are made, in order to avoid the conflict between the first generation biofuels and food supplies as well as to restrict the uncontrolled waste disposal and volume of wastes.

The battle with human made waste is dated back many centuries, since the dawn of civilization. When human left his wild nature and started to live in communities fulfill his everyday activities, the issue of waste management began to take form and be the source of severe for the humanity and environment impacts.

In many stages of human's evolution, wastes have been a significant factor of grave events in history. A characteristic example of the role of wastes is the plague that struck Europe the Middle Age (1348-1350), that took a pandemic form and decimated over one third of the European population. The so called "Black Death" was caused mainly by a bacterium which was transported to humans by rats that were living in wastewaters and solid wastes accumulated in the cities. From the grave plague of Justinian in Egypt in 542AD to this in Athens in 430BC and from this to the second pandemic in Middle East and Europe in 134AD, the grave fire in London, to Vietnam in 1960AD, the effects of non-proper treatment of wastes are visible during the whole historical path of humanity [5] [6].

Waste management was first introduced in Knossos, in the Greek island of Crete, in 3000BC where big fosses as well as a sewer system for rain and waste water, were constructed in order for the solid wastes of the city to be disposed of and the waste waters to be drained, respectively. Similarly, in Athens in 500BC, a specific law commanded that wastes should be deposited more than a mile out of the town because the piles of rubbish next to the city walls provided an opportunity for invaders to scale up and over the walls [7]. Rome had similar problems, and eventually developed a waste collection program in 14 AD [8].

For the upcoming centuries until our days, people tried to employ methods for an integrated waste management. With the passage of time, the technics of waste treatment have been changed in accordance with the development of consuming products and consequently the change of the wastes' composition with the increase of inorganic materials such as paper, paper packaging, plastics and ferrous metals [9].

A recent report indicates that the intensive increase of urbanisation coupled with the increase of consuming demands and technological evolution of modern societies, the increase of industrialization, are considered to be the basic reasons for the extensive production of municipal wastes [10]. Furthermore, it has been noticed that this the waste production varies among countries according to their national income, GDP,

stage of development, culture, geographical and climatic conditions. More specifically, countries with income lower than US$ 5000 generate an also low amount of MSW (Municipal Solid Wastes) which ranges between 0.3 and 0.9 kg/capita/day. While in higher income countries this amount ranges between 1.4 and 2.0 kg/capita/day. The linear relation between the GDP and the daily waste production per capita for low income countries, such as India and Egypt, to medium and high income countries like USA, is presented in **Figure 1** [11].

Figure 1. Countries income and the rate of generated MSW (UNDESA, 2010).

The composition of MSW is another factor that varies among the developed and developing countries, with the amount of organic matter, in the former, not exceeding the average of 30% of the total produced waste, while the respective amount in the latter reaches 58% of the total generated MSW based on the **Figure 2**, where the different composition of MSW in the OPEC and non-OPEC countries is indicated [11].

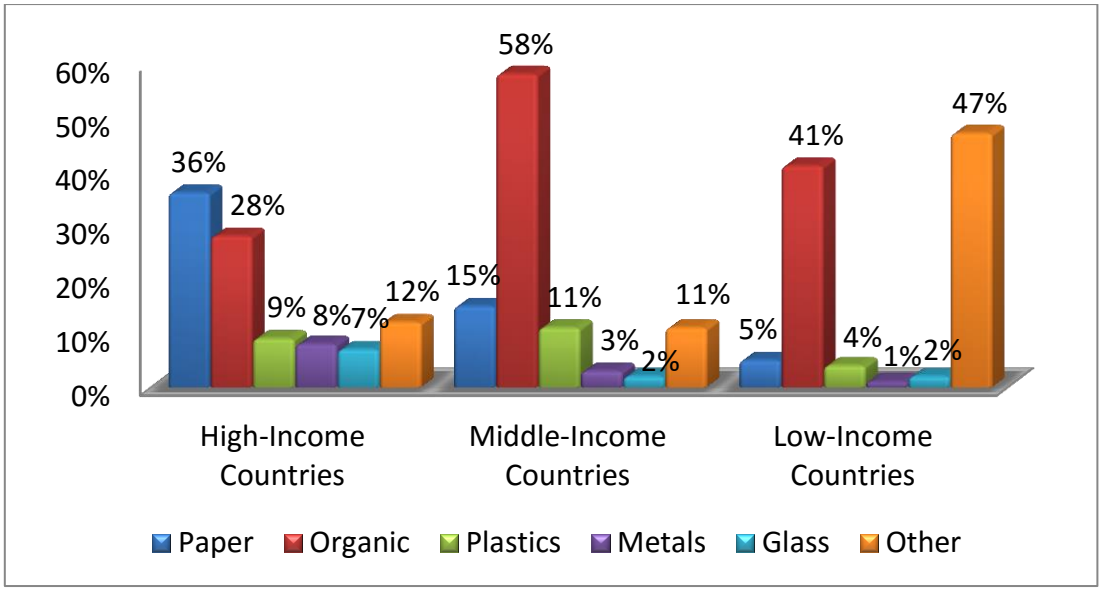


Figure 2. Characteristics of MSW streams depending on income (UNDESA, 2010).

Municipal Solid Wastes (MSW) along with Liquid Wastes consist a serious environmental problem worldwide, because of the extensive pollution of the atmosphere, the soil and the surface and underground aquatic systems contamination. First of all, MSW landfills and Wastewaters can easily be infectious agents as severe diseases such as typhus, cholera, malaria, yellow fever, hepatitis, encephalitis, gastroenteritis, and dysentery which grow in these areas can be transmitted via mosquitoes, flies and rats to human.

Additionally, combustible and toxic materials, such as oils, fertilizers, solvents which produce SO_2, hydrocarbons and polycyclic aromatic hydrocarbons and other hazardous gas emissions which include methane and volatile organic compounds, mostly hydrocarbons, feature these areas as totally carcinogenic, mutagenic and toxic for the human health and environment. For instance, according to USEPA, in 2008 landfills contribution to total world methane production, which is a powerful greenhouse gas, was 23% **[12]**.

Moreover, water, groundwater and soil contamination is a consequence of the uncontrolled leaks and disposal waste in landfills and waters that contributes in biodegradation as well. The levels of this pollution depend on the composition of both solid waste and sewage sludge and mostly the BOD (Biological Oxygen Demand) and COD (Chemical Oxygen Demand) amounts. High levels of BOD determine that water and solid quality is rapidly decomposed of biodegradable organic matter and the

depletion of dissolved oxygen, while COD monitors the total organic matter [13] [14]. More specifically, **Table 1** indicates the compositional ranges for numerous leachates from MSW landfills, where the BOC, COD, TOC (Total Organic Carbon) and TDS (Total Dissolved Solids) levels of municipal solid waste range is 480-72,500mg/l, 0-195,000mg/l, 335,000mg/l and 584-55,000mg/l respectively. This amount of components tends to increase over time [15] [16] [17] [18] [19].

Table 1. Chemical composition of leachate from municipal solid waste.

Parameter	Concentration range (mg/l)	Parameter	Concentration range (mg/l)
Alkalinity (as $CaCO_3$)	0–20,850	Nitrogen (ammonia)	0–1250
Aluminum	0.5–85.0	Nitrogen (nitrate)	0–9.8
Antimony	0–3.19	Nitrogen (nitrite)	0–1.46
Arsenic	0–70.2	Nitrogen (organic)	0–1,000
Barium	0–12.5	Nitrogen (Kjeldahl)	0–3,320
Beryllium	0–0.36	Nickel	0–7.5
BOD	480–72,500	Phenol	0.17–6.6
Boron	0.413	Phosphorus (total)	0–234
Cadmium	0–1.16	Phosphate	0.01–154
Calcium	5–4,080	pH	1.5–9.5
Chloride	11,375	Potassium	0.16–3,370
Chromium	0–22.5	Selenium	0–1.85
COD	0–195,000	Silver	0–1.96
Conductivity (μmho/cm)	480–72,500	Sodium	0–8,000
Copper	0–9.9	Thallium	0–0.32
Cyanide	0–6	Tin	0–0.16
Fluoride	0.1–1.3	TDS	584–55,000
Hardness (as $CaCO_3$)	0.1–225,000	TSS	140,900
Iron	0–42,000	TOC	335,000
Lead	0–14.2	TVA(as acetic acid)	0–19,000
Magnesium	0–115,600	Turbidity	40–500
Manganese	0.05–1,400	Sulfate	0–1,850
Mercury	0–3	Zinc	0–1,000
Organic halides	0.320–3.5	Phenols	0–4
Benzene	0.1–0.6	Toluene	0–3.2

Research also summarizes that many chemical compounds have been also detected in Sewage Sludge (SS) procured from sewage treatment plants. **Table 2** presents the initial physicochemical characteristics of SS, with BOD and COD to be about 580mg/l and 1,500mg/l, respectively [20].

Table 2. Initial physico-chemical characteristics of SS before composting.

Parameter	Sewage sludge (SS)
pH	6.88 ± 0.1
EC (S/m)	0.28 ± 0.08
Ash content (%)	42.16 ± 0.5
TOC (%)	33.54 ± 0.44
TN (%)	1.31 ± 0.1
TP (g/kg)	7.97 ± 0.1
C/N	25.6 ± 1.5
COD (mg/L)	1500 ± 75
BOD (mg/L)	580 ± 15
Fe (%)	0.63 ± 0.03
Cu (mg/kg)	158.2 ± 20
Mn (mg/kg)	290.6 ± 30
Zn (mg/kg)	612 ± 45
Pb (mg/kg)	49.4 ± 6
Na (%)	0.5 ± 0.05
K (%)	0.86 ± 0.56
Ca (%)	5.39 ± 0.68

Finally, energy overconsumption is another impact of the increase of waste disposal further from inhabited areas due to the complex and lengthy routes that vehicles should cover, that also increase air pollution [11].

The non-proper and unsustainable waste management not only damage the environment but also affects the human health and activities. Thus, a modern sustainable waste management system must be:

- **environmentally effective**, so to reduce as much as possible the emissions to land, air and water such as CO_2, CH_4, SO_x, NO_x, BOD, COD and heavy metals
- **socially accepted** by the majority of people in the community and
- **economically viable**

It should also concern the possibilities of reducing the products (prevention) and making use of them, through re-use methods, recycling and energy recovery.

Technologies aiming to exploit wastes in order to recover energy, decrease depletion of fossil fuels, decrease pollution and reduce waste disposal were developed over the years. The process of Waste-to-Energy (WtE) for energy regeneration through direct

combustion of waste or production of combustible fuels such as methane, hydrocarbons and other synthetic fuels via incineration and gasification technologies, is used efficiently in a worldwide scale. Until 2003, 130 million tons of MSW were combusted every year in 600 WtE facilities all around the world [21]. Today, there are 1600 WtE facilities around the world [22].

In 2012, a World Bank's evaluation assessed that the annual global MSW production was 1.3 billion tons which corresponds to 1.2 kg/capita/day. This was a rough estimation without taking into account the fact that the per capita waste generation depends on the urbanisation and GDP levels, as it was referred above [23]. The Afval Energie Bedrijf CHP plant in Amsterdam is a great example of WTE incineration technology. This type of plant, which has been operated since 2007, is the largest of its kind around the world, with 114.2 MW installed capacity, up to 30% electricity production efficiency and with the ability to cope with large quantities of MSW that reach the 1.5 million tons/year [24]. Likewise, China, that suffers from an atrocious air quality motivated by the rapid ascend of population, which rised by 43% from 1978 to 2008 and subsequently the increase of the MSW generation by 55% during the same period, succeeded 0.15 tons net emission reduction of carbon equivalent per each ton of MSW due to WtE management of waste in 2003 [23]. Today, the 17% China's total amount of produced MSW (23 million tons) is processed in the approximately 100 WtE plants that the country occupies [25] [26]. Regarding the emissions generated, According to a field study in various major cities in the country, the WTE plants have significantly low emissions of dioxins and mercury, which were far beneath the EU 2010 standards [26].

In general, since 17th of June 2008, the EU Parliaments considers the WTE as an energy recovery operation, with Switzerland, Sweden, Netherlands, Denmark, Germany, France and Belgium being the first countries applied this method. [27].

This technology is confirmed to be an effective solution for the waste management issue and environmental friendly, in the same time [27].

As reported by the Confederation of European Waste to Energy Plants (CEWEP), in 2009, 70 million of MSW were preceded in WtE facilities all around Europe, producing electricity of 28 billion kWh and heat of 70 billion kWh, which estimated to substitute 7 to 38 million tons of fossil fuels (gas, oil, hard coal and lignite).

Replacing these fossil fuels, WtE plants are able to provide with electricity and heat about 13 million and 12 million inhabitants per year, respectively [28]. On the contrary, Greece is quite behind the evolution. In our country, nearly the only method of MSW management is the disposal to waste landfills. Hence, we must conform to the new EU Directive 2008/98 which prescribes that WTE must be included in the Waste Treatment process in all Europe [27].

Greece lacks of development not only in waste treatment but in energy production from biomass as well. The uncontrolled disposal of huge amounts of solid and liquid wastes burdens the country environmentally, socially and also economically. Contamination of soil, water and air along with the jeopardization of people's health and also the expenses of energy imports and fines charged due to non-conforming with the European's regulations, are considerable issues society has to cope with. In 2010, the contribution of biomass in the total energy production from RES was 1.13%, with 0.81TWh produced energy. The country aims is reach the goal of generating of 1,745GWh of electricity, 1,222,000 toe (tons of oil equivalent) for heating and cooling and 617,000 toe of biofuels, until 2020 [29] [30]. These promising steps, in the energy sector intent to exploit agricultural, animal, industrial, forestry residues and industrial and municipal wastes in order to produce biofuels and energy of about 23TWh until 2020 as well as contributing to the energy requirements of the country, which were reported to be approximately 56.4TWh, in 2012, in sectors of industry, household, agriculture and electricity production [29].

Hence, in response to these ambitions the objective of the thesis is to identify the current situation of Waste Management in Greece and evaluate the potential of energy production from municipal wastes and other alternative fuels, in Greece via WTE technology, which, as in many countries in the world, should be a major part of the modern integrated waste management system, in order to generate renewable energy for use and contribute to the reduction of the waste amount and the pollution volume, as well. The case study of the thesis concerns the modelling of an energy production system from alternative fuels through the COCO (CAPE-OPEN to CAPE-OPEN) Simulator software for the design and operation of chemical processes and finally the presentation and assessment of those results.

2. Municipal Wastes

2.1 Municipal Waste Definition

Municipal Wastes are either solid or liquid wastes produced in urban areas, commercial facilities and institutions. The term “waste” depicts an unwanted and undesirable material [31] [32].

The organic portion of municipal solid wastes as well as the dried sludge resulting from the biological waste water treatment is characterized as municipal waste biomass, which is biodegradable [33] [34]. As reported by Eurostat in 2012, the definition of Municipal Waste describes the wastes generated by households as well as other similar waste sources such as the commercial sector, offices and public institutions. The amount of municipal waste produced consists of waste collected by or on behalf of municipal authorities and disposed of via the waste management system of the society [35].

2.1.1 Municipal Solid Waste

Municipal Solid Waste (MSW), due to its composition, can be classified into (a) Organic Solid Waste (OSW) and (b) Inorganic Solid Waste (ISW). Organic Solid Waste or Biodegradable Municipal Solid Waste (BMSW) is waste from households and commercial activities that can undergo a biological decomposition process. This category includes food and garden wastes, paper and cardboard. Inorganic Solid Waste is characterized by non-biodegradable matter, which on the other hand can be combusted depending on the nature of the material they constitute. This category constitutes rocks, plastics, metals, glasses etc. [31] [32].

Solid wastes can generally be categorised in municipal solid waste, construction waste and special waste as **Figure 3** demonstrates. These groups can also be categorised further. According to the Directive 99/31/EC, the Municipal Solid Waste term includes the household and other waste of similar nature and composition, such as waste from commercial activities, offices and institutions (schools, hospitals, government buildings etc.). It also includes bulky waste (mattresses, furniture etc.) and garden waste, leaves, twigs, vegetables, as well as waste from cleaning the streets.

Manure and dry sludge from sewage treatment also are included in urban waste [34] [35].

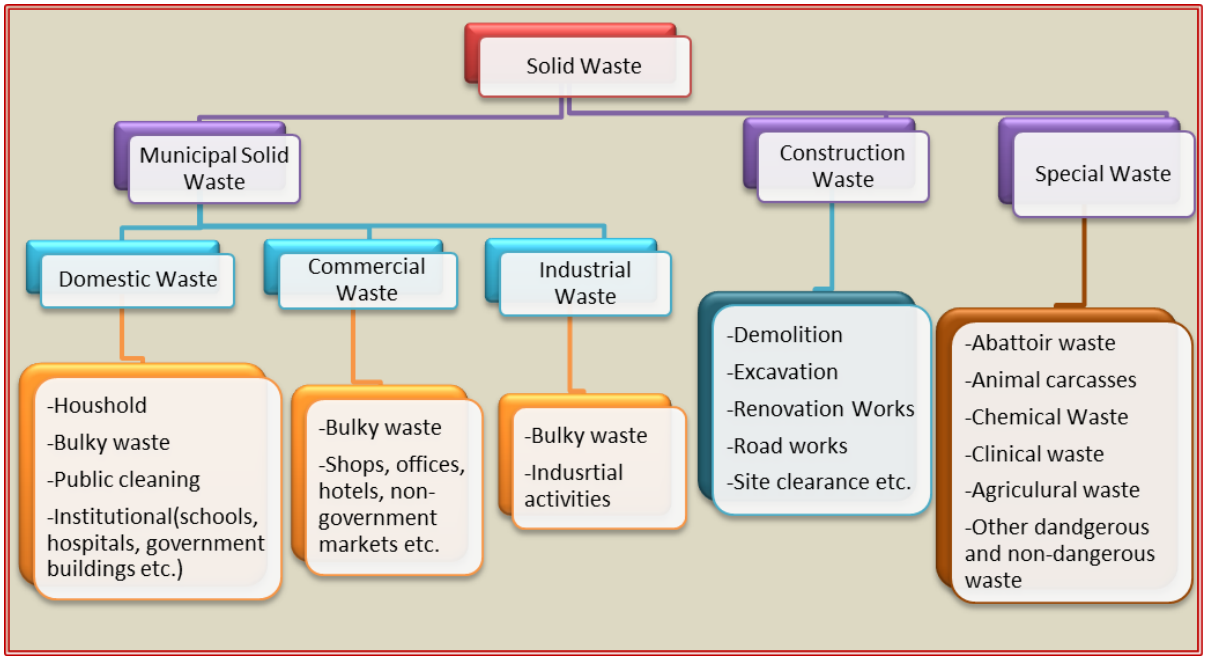


Figure 3. Solid Waste Classification.

2.1.2 Municipal Liquid Waste

Municipal Liquid Wastes, also known as wastewaters or sewage are produced from the urban environment and consist of:

(a) Sanitary Sewage which is the domestic sewage that includes human wastes from toilets, baths, laundry, lavatory, and kitchen wastes from homes, public buildings , commercial and industrial facilities. Sanitary Sewage consists of 99.9% of water and 0.1% of impurities. In general, the pre-treated Sanitary Sewage is characterized by a BOD at 200-250 mg/l, a COD at around 500 mg/l and TSS at 220-240 mg/l along with 35 mg/l of N and 10 mg/l of P and a great amount of pathogenic bacteria.

(b) Industrial Sewage which is produced from manufacturing activities and it contains 360-14,000 mg/l BOD, 1,400-21,100 mg/l, a COD and 540-1,250 mg/l TSS. The range of the concentrating values depends on the type of industry that generates the wastewaters.

(c) Storm Sewage which is wastewaters by rainfalls, and which transports organics, suspended and dissolved solids, and other ferrous substances [36] [37].

2.2 Municipal Waste Treatment

Due to the excessive air and soil pollution as well as the surface water and ground water contamination along with the overconsumption of water and energy the European Parliament introduced two critical Directives. In 23 October 2000, European Parliament established the EU Water Framework Directive (Directive 2000/60/EEC) in the field of water policy in order to secure good quality and quantity of all water bodies, including marine waters up to one nautical mile from shore, by 2015. Additionally, in 17 June 2008 the Waste Framework Directive (Directive 2008/98/EEC) was introduced and it inserted the term of "waste hierarchy" in order to promote and set as priority the waste prevention and as ultimate step the waste disposal, and mainly landfilling, of an amount of wastes as reduced as possible [35] [38] [39].

2.2.1 Municipal Solid Waste Treatment

The integrated municipal waste management system that was defined with the Waste Framework Directive, includes an optimized collection system, the reduce of waste production, implemented transportation systems, sorting at source, recycling of the separated materials, economically effective transshipping system with the ultimate goal the energy recovery, the reuse of the materials and the final disposal of the residual and the reduced volume materials to contemporary Residues Landfills (RL). The "waste hierarchy" and the connection between these processes are presented in Figure 4 [40].

According to Ministerial Law 29407/3508 *"the waste disposal in SL, with no further processing, is not permitted"*. In accordance with this waste processing is defined as the sorting at source, the mechanical sorting in centers of sorting of recyclable materials, the transshipping and packaging, the thermochemical and biochemical conversion technologies and the final disposal at landfills [33] [34]. In general the basic steps for an integrated municipal solid waste treatment are:

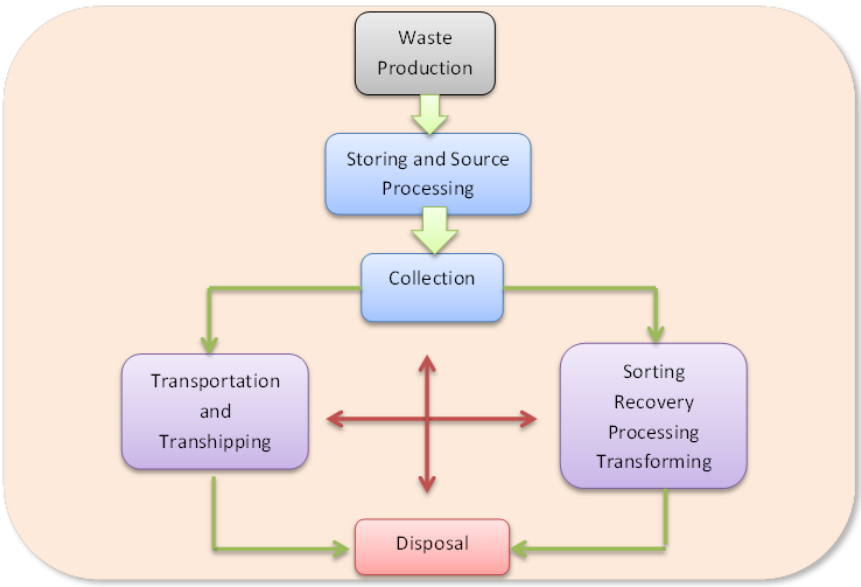


Figure 4. Connection between the subsystems of a solid waste treatment system.

(a) Prevention and Reduction

Prevention is one of the most important methods to reduce the quantity of waste produced in its source. It contributes to the minimization of the quantity, the cost of the subsequent management and environmental impacts of uncontrolled waste disposal. Prevention and reduction can be succeeded by being applied during the whole life cycle process of products, through the design, production, packaging and distribution of products with the lowest possible volume, toxicity and highest life time [32] [40].

(b) Reuse

With reuse process discard materials can be reproduced for use and consequently the quantity of wastes is decreased. It more preferable to recycling as it does not require the same material to undergo through a detailed treatment process thus reducing the needs for energy and material usage [32] [40].

(c) Recycling

Recycling includes a treatment of discard waste materials in order to be reused in an advanced or their initial form. Although it concerns the treatment of organic wastes for reuse it excludes energy recovery. The advantage of this process is that there is a variety of material that can be recycled [32] [40].

(d) Energy Recovery

Energy recovery from wastes is the process of producing energy in the form of electricity, heat and fuels. This process offers the possibility to reduce significantly the volume of waste disposed in landfills, pollution and secure energy supplies. The last few decades waste to energy technologies have been developed for integrated municipal waste treatment. Biomass from waste can be used to meet energy needs such as heating, cooling, electricity, etc. either by direct combustion, either by transforming into gases, liquids and/or fossil fuels through thermochemical or biochemical processes [41] [42].

1. Thermochemical Conversion
    - Biomass Combustion/Incineration
    - Biomass Gasification
    - Pyrolysis
2. Biochemical Conversion
    - Anaerobic Digestion
    - Aerobic Digestion

In the following chapter these conversion technologies will be explained.

(e) Disposal/Landfilling

The final stage of an integrated municipal waste treatment is the residue disposal in landfills. There are wastes no more but residues generated from the whole treatment. The reduced, non-toxic and remediated residues are disposed in residue landfills with fewer impacts.

2.2.2 Municipal Wastewater Treatment

The methods of wastewater treatment are divided in four main categories and illustrated in **Figure 5**:

(a) The Preliminary Treatment

During this stage, the removal of coarse solids and other large materials in most cases found in wastewaters, takes place. Coarse screening and grit removal are the operations occur in this first stage for medium to large wastewaters treatment plants. In case of smaller facilities the latter activity is not included. The solid materials are removed in the form of sludge and disposed in landfills.

(b) Primary treatment

During primary treatment, sedimentation and skimming occur in order to remove sedimentary organic and inorganic solids and floating materials respectively. In most cases this primary unit includes biological treatment via anaerobic digestion process, during which gases are produced and contain approximately 60-65% methane that can be used as energy recovery source. The advantage of this stage treatment is the removal of 25-50% of BOD, 50-70% TSS and 65% TOC.

(c) Secondary/Biological treatment

Primary treatment could be considered sufficient in case of wastewaters from irrigation. However, in case of human liquid wastes a secondary treatment, for a further treatment, is requisite. In essence, this second unit is a subsequent biological process to the former aiming to remove organic matter and solids residues via an aerobic digestion process. The combination of primary sedimentation and secondary biological treatment offers a final effluent free of organic and inorganic sediments, material and heavy metals. A typical combined unit discards approximately 85% of BOD and TSS.

(d) Tertiary/Advanced Treatment

Activated sludge consisted of components that are not removed through the secondary treatment, such as nitrogen, phosphorus, additional suspended solids, refractory organics, heavy metals and dissolved solids can be discharged in the tertiary treatment. Sometimes, tertiary treatment can be a combination of the two preceding or used to replace the secondary one.

Final step of municipal wastewater treatment is the disinfection of the sludge by injecting chlorine solution at the head end of a chlorine contact basin. The final dried

sludge disposed eventually in landfills or reused as fertilizers, or as forests, parks and gardens recreation. [31] [37] [43] [44].

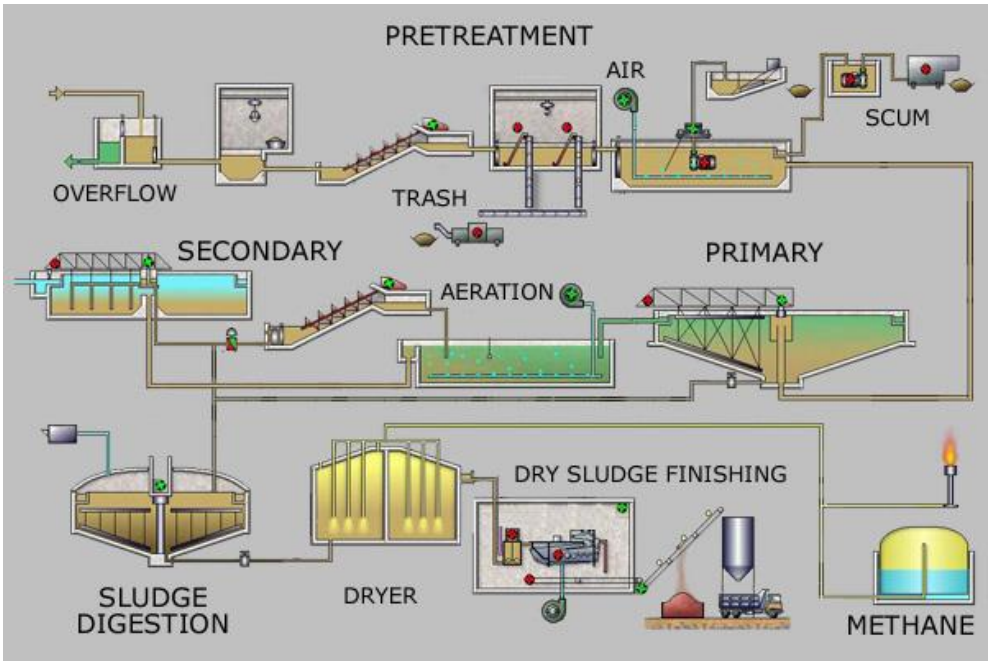


Figure 5. Municipal Wastewater Treatment.

2.3 Municipal Wastes in Europe and Greece

Since 1995, the application of the waste policy and the introduction of an advanced municipal waste system in accordance with the technology developments have resulted in great performances, in the waste management sector, in the majority of the countries all around the world. More specifically, according Eurostat's data publication, given in **Table 3**, the evolution of municipal waste production in Europe from 1995 to 2013, the progress in waste reduction in many countries in Europe is obvious. More conveniently, **Figure 6** places in decreasing order countries by their municipal waste generation for the 2003 to 2013 period [35] [45].

Table 3. Municipal waste generated by country in selected years (kg per capita).

	1995	1999	2003	2007	2010	2013	change (%) 1995-2013
EU28				523	503	481	
EU27	473	511	514	524	504	481	2%
Belgium	455	465	468	494	455	439	-4%
Bulgaria	694	598	603	553	554	432	-38%
Czech Republic	302	327	280	294	318	307	2%
Denmark	521	577	598	707	673	747	43%
Germany	623	638	601	582	602	617	-1%
Estonia	371	412	414	449	305	293	-21%
Ireland	512	577	730	772	624	586	14%
Greece		392	427	448	531	506	51%
Spain	510	613	646	578	510	449	-12%
France	475	507	506	543	533	530	12%
Croatia				399	379	404	
Italy	454	498	524	557	547	491	8%
Cyprus	595	620	670	704	696	624	5%
Latvia	264	256	304	391	324	312	18%
Lithuania	426	351	389	419	404	433	2%
Luxembourg	587	646	678	695	679	653	11%
Hungary	460	483	464	457	403	378	-18%
Malta	395	476	580	654	601	570	44%
Netherlands	539	582	586	606	571	526	-2%
Austria	437	563	607	597	562	578	32%
Poland	285	319	260	322	316	297	4%
Portugal	352	433	449	471	516	440	25%
Romania	342	314	353	391	324	272	-20%
Slovenia	596	550	418	525	490	414	-31%
Slovakia	295	261	281	294	319	304	3%
Finland	413	484	466	506	470	493	19%
Sweden	386	428	464	493	445	458	19%
United Kingdom	498	569	591	567	509	482	-3%
Iceland	426	454	484	558	306	345	-19%
Norway	624	594	402	491	469	496	-21%
Switzerland	600	635	667	720	708	702	17%

As it is noticeable from **Table 3** and **Figure 6** above, there is a significant variation of the amount of municipal waste produced between the countries. For instance Denmark displays a waste production of 747kg/capita while Romania exhibits an amount of 272kg/capita for the same year period, 2013 [45].

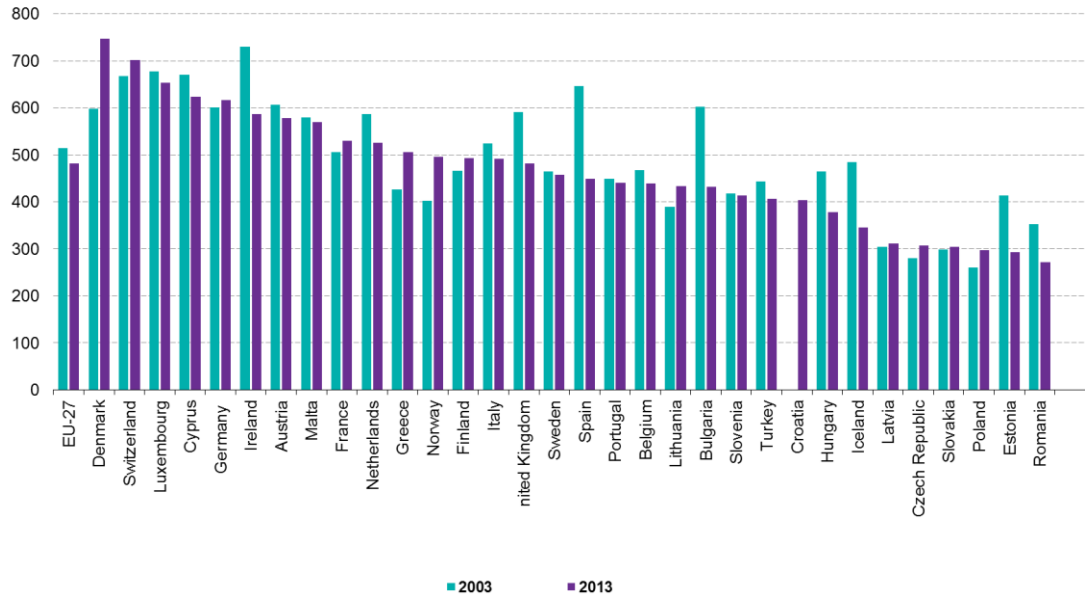


Figure 6. Municipal waste generated by country in 2003 and 2013, sorted by 2013 level (kg/capita).

These variations mainly reflect differences in consumption motives and economic growth between the countries, but also depend on the way that municipal waste is collected and managed. These variations are due to a combination of reasons such as the different composition of municipal waste. This means that a country with high bulky or garden waste content in its municipal waste composition will appear to produce more wastes than another country which excludes these parts. Moreover, the differences regarding the sources of wastes are also an explanation for these variations. For example, some countries include only waste from households, while other countries include waste from commercial activities, trade, administration and offices collected and managed along with households' waste. Additionally, the collecting and managing system also varies from place to place, so some countries may include separately packaging waste from households, in contrast with other countries which do not [35] [45].

Table 4. Municipal waste generated by country in selected years (kg/capita).

GEO/TIME	2005	2006	2007	2008	2009	2010	2011	2012	2013
Denmark	662	666	707	741	693	673	789	759	747
Cyprus	688	694	704	728	729	696	683	670	624
Ireland	731	792	772	718	651	624	617	587	586
Luxembourg	672	683	695	697	679	679	666	652	653
Malta	623	624	654	674	649	601	589	588	570
Netherlands	599	597	606	600	589	571	568	549	526
Austria	575	597	597	600	590	562	573	579	578
Bulgaria	588	577	553	599	598	554	508	460	432
Germany	565	564	582	589	592	602	614	619	617
Italy	546	559	557	552	543	547	529	504	491
Spain	588	590	578	551	542	510	485	468	449
Slovenia	494	516	525	542	524	490	415	362	414
France	530	536	543	541	535	533	538	535	530
United Kingdom	581	583	567	541	522	509	491	477	482
European Union (28 countries)	516	522	524	521	511	504	498	489	481
Finland	478	494	506	521	480	470	505	506	493
Portugal	452	465	471	518	520	516	490	453	440
Norway	426	459	491	487	470	469	485	477	496
Sweden	477	490	486	483	470	439	451	452	453
Belgium	483	485	494	479	467	456	456	450	439
Greece	437	443	448	454	461	531	503	506	510
Hungary	461	468	457	454	430	403	382	402	378
Lithuania	387	405	419	428	381	404	442	445	433
Croatia	336	384	399	415	405	379	384	391	404
Romania	383	396	391	411	381	324	268	271	272
Estonia	433	398	449	392	339	305	301	280	293
Latvia	320	343	391	345	352	324	350	301	312
Poland	319	321	322	320	316	316	319	317	297
Slovakia	273	284	294	313	307	319	311	306	304

According to Table 3 and **Figure 6**, we can observe that 18 of the 31 countries displayed an increase in municipal waste produced per capita from 1995 to 2013, whereas 6 of them had a relatively steady raise. Greece's data stars from 1996, where it recorded the highest average annual growth rates at 2.3%, followed by Malta and Denmark at 2.1% and 2.0% respectively. For the remaining countries the total increasing trend was stabilized around 2003 and 2007. For instance, in Austria, Ireland and Sweden, the amounts were stabilized around 2003 and start falling slightly between 2003 and 2013. The fluctuation in waste generation observed these years is due to the economic situation, the population growth and the operation of an efficient or inefficient waste management system [35] [45]. Additionally, as the technics for a municipal waste management system were completed after 2004, we notice such dissimilarities over the years. The data from 2005 to 2013 in **Table** 4 are defined more accurate [35].

Table 5. Categorization of municipal waste from Ministry for the Environment, Energy and Climate Change 2011.

Municipal Solid Wastes (MSW)				**Municipal Liquid Wastes (MLW)**
Composition		LHV (kcal/kg)	Energy (kcal/100kg MSW)	HV
Organics (food residuals, yard trimmings, etc.) Paper/Cartons Plastics Metals Glass Inserts Other	40% 30% 14% 3% 3% 2% 8%	1,100 3,960 7,700 165 33 4,400 5,770	53,900 79,300 65,450 742 748 13,200 31,735	3,300kcal/kg, 13.8MJ/kg, 3.8kW/kg
Conversion to energy through direct combustion or anaerobic digestion				Sludge from the sewage treatment is a raw material for biogas production

The European Union started its downward trend after 2007, to an average total municipal waste production at 243.26 million tons which corresponds to 481 kg/capita in 2013. On the other hand, in our country this amount reached the 5.58 million tons of Municipal Solid Waste (MSW), corresponding to 510 kg/capita in the same year as illustrated in Table 4 [45]. The composition of municipal waste between our country and Europe varies significantly. **Table 5** illustrates the categorization of municipal waste, its composition and calorific value, in Greece, as well. As it is obvious the highest quota of 40% is occupied by the total organic waste, from which the paper fraction consists the 30% of waste composition followed by plastics at 14%. According to **Figure 7**, where the average composition of urban waste in both Greece and Europe from the Ministry for the Environment, Energy and Climate Change in 2011 is presented, we can observe that in comparison with the average composition of municipal waste in European Union, in Greece there is greater participation of organic waste and smaller quantities of packaging waste [46]. The reasons of these differences were explained in the previous subsection.

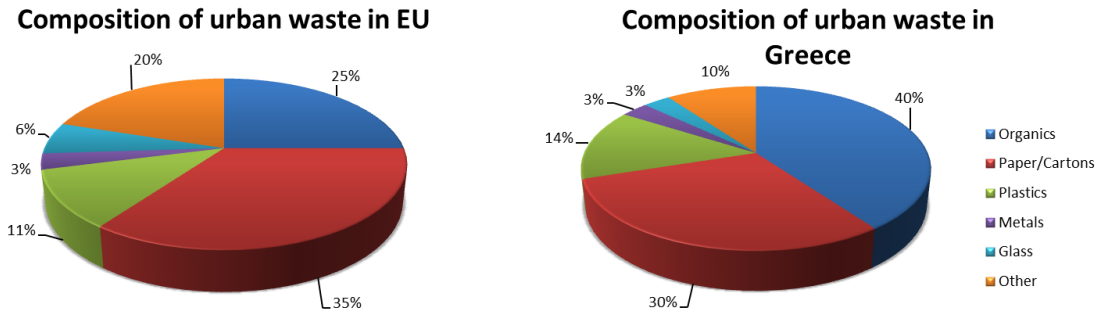


Figure 7. Composition of MSW in Greece and EU from Ministry for the Environment, Energy and Climate Change.

MSW differ in terms of quantity and quality. The main factors affecting this variety are the demographic characteristics of each region, the macroeconomic data, such as GDP and consumption, the technological development, the seasoning and the standard of living [47] [48]. A great example of this variation is evident in **Figure 8** with the percentage of the participation of regions in the national production of municipal waste. According to this, the highest MSW production occurs in Attica and especially in the capital city, Athens, where the daily production is around 6,500 tons. Attica produces a total of 2.4 million tons annually, from which 95% is deposited in the Ano Liosia Sanitary Landfill, which is already overloaded and which, despite the decision and studies in order to be abolished, is still in arbitrary operation. In fact there is a supplementary landfill, the Filis Sanitary Landfill, which is adjacent to the former, thus the problem continues to exist **[**49] [50] [51]. Attica produces the highest amount of MSW, at 43.75%, in the whole country, followed by Central Macedonia at 16.39% [34] [50].

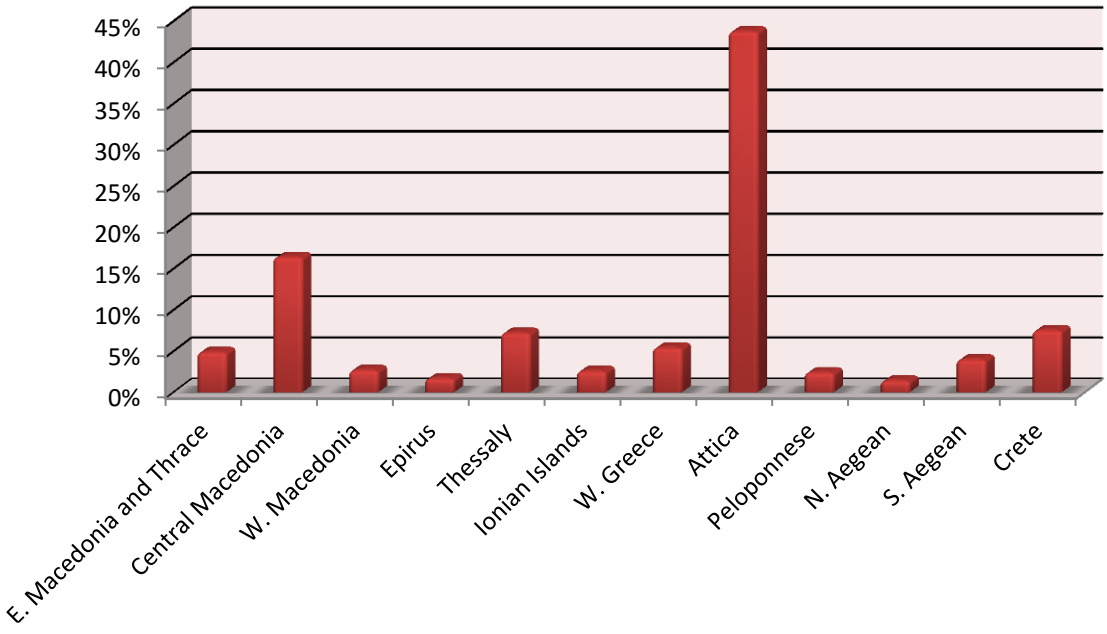


Figure 8. Percentage of the participation of regions in the national production of municipal waste from Ministry of Environment, Planning and Public Works, 2012.

Today, in Greece, the daily generation of MSW is about 15.000 tons which corresponds to about 5.58 million tons of Municipal Solid Waste (MSW) that are produced annually [52] [53]. This amount is higher than the predicted amount of 5.2 million tons that our country would have reached in 2016 [51] [54]. Hence we can understand that the problem of the MSW rise is still crucial despite the efforts for reduction through recycling.

Over time, the increase of urbanisation, the evolution of the great urban centers and the rise of living standards result in increasing consumers' habits and demands which leads to an aggressive growth of MSW production. In essence, since 2001 to 2009 the production of MSW in Greece displayed a constant increase of about 75,000 tons per year, which corresponds to 1.5% increase annually. As **Figure 9** indicates, there has been recorded an increase from 416 kg of MSW/capita in 2001 to 531 kg MSW/capita in 2010 [50]. According to Eurostat in 2013, the total MSW production in European Union was 219 million tons annually with 481 kg per year per inhabitant, while Greece generated annually 5.2 million tons of MSW, with an average production of 506 kg MSW/capita/year [55]. This means that the production of municipal solid waste in our country corresponds to 7.4% of the total production in Europe [47]. More specifically, the average daily production of municipal waste per capita in our

country, in 2013, was 1.38 kg/capita, while the equivalent amount in EU was 1.2 kg/capita/day.

In general, as it has already referred in the previous chapter, the volume of waste produced is directly related to the economic growth, or growth in production and consumption and technological development. GDP (Gross Domestic Product) is the driving force for waste generation. The highest the GDP, the highest the MSW production is. However, a High GDP figures a more developed technology in waste treatment and reduction of its volume finally disposed. In case of Greece, the GDP that was recorded in 2014 was 237.58 USD Billion which is significantly lower than other European countries like Germany and with United Kingdom (UK) a GDP of 3852.56 USD Billion and 2941.89 USD Billion respectively. This high GDP is one of the reasons why despite the high MSW production in Germany, 617 kg/capita, and UK, 482 kg/capita, the final disposal is only 1 kg/capita and 165 kg/capita, respectively, whereas in our country with the low GDP and lack of developed waste treatment and energy recovery technologies, the waste disposal and production are higher than in Europe [11].

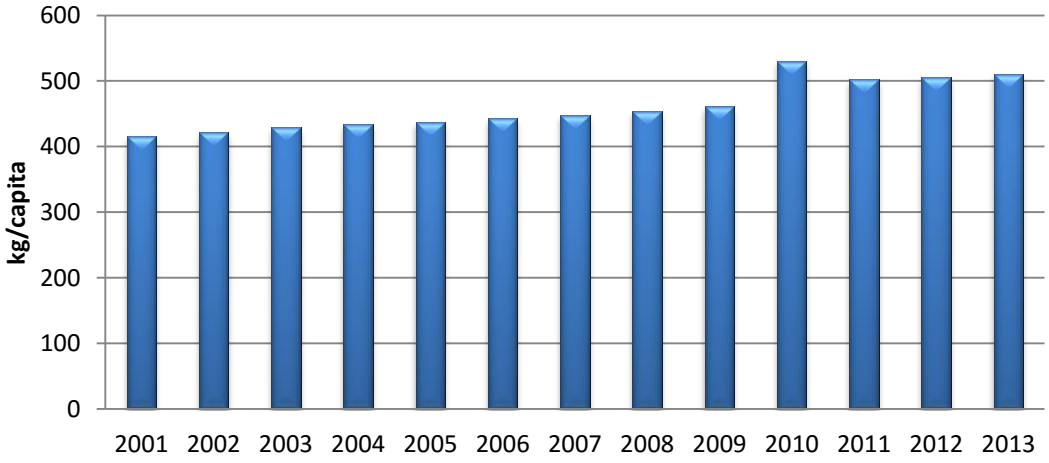


Figure 9. MSW generation per capita in Greece (Eurostat, 2013).

2.3.1 Municipal Solid Waste Treatment in Greece

In Greece, until the end of 1990, we could meet an uncontrolled disposal of MSW in waste disposal sites. Few years later the first system of collection and transportation of MSW was introduced, while the first waste management sites started to be constructed. Today, the majority of Greece's regions occupy integrated collection and transportation waste systems.

The problem is that in Greece, as in many other European countries, the most common and basically the dominant method of Municipal Solid Waste management still remains the territorial disposal, with no further processing. More accurately, the main projects constructed in the country, for this purpose, are the Sanitary Landfills (SL) and the Uncontrolled Waste Disposal Sites (UWDS). In 2001, the total amount of MSW landfilled was the 91%, while only the 8% was recycled. More recently, in 2010, this amount was decreased by 10% and reached the 81% as recycling, was increased, after 2007, at 20% of the total produced MSW [33] [34] [52]. From 2007 to 2013 the 81% of MSW ends up to the 71 SL that the country occupies [56] [57].

In case of UWDS, the open dumping of wastes causes adverse effects on the environment, the human's health as long as other disturbances (aesthetic, fumes etc.). Thus, according to the institutional framework the operation of UWDS was characterized as extremely hazardous and it should be prohibited. The Ministry for the Environment, Energy and Climate Change established the National Plan of Solid Waste Management, which was instituted by Ministerial Law 50910/2727/03 (FEK 1909B') and set a clear timetable for this elimination until 2008. Hence, the UWDS started to be replaced gradually by modern SL, with an initial goal of the temporary operation of a single uncontrolled disposal space per Municipality and eventually the gradual elimination by 2008. The program of replacement of UWDS is still in full progress with 293 UWDS still operating, for which the fine from the EU is 54.450 per day, and 2.291 in restoration process [56] [58] [59] [60].

According to Eurostat 2012, in Europe, the 27% and 15% of the treaded municipal waste was recycled and composted respectively, while the 34% was landfilled and the 24% was incinerated. The highest amounts of municipal waste treatment are recorded in Germany (65%), Austria (62%), Belgium (57%) and Netherland (50%). Regarding

incineration of waste, dominant countries are Denmark and Sweden (52%), followed by Netherland (49%), Belgium (42%) and Luxembourg (36%) [61].

2.3.2 Municipal Wastewater Treatment in Greece

Today, in Greece, it is estimated approximately 350 Municipal Wastewater Treatment Plants (MWTP) to be occupied and serve about 65% of the permanent inhabitants of the country. From this amount about the 88% are activated sludge plants, 10% natural systems, and 2% attached growth while 1% provides primary treatment. From the activated sludge plants the 85% are extended aeriation systems, 10% are conventional systems and 5% are sequencing batch reactors. Extended aeriation is the technology the most dominant and suitable to the climate of our country in order to succeed efficient sludge decomposition. Regarding the disposal of the treated effluent, in Greece for many decades, sea outfalls were being used, as the majority of MWTPs was built in short distances from the sea shores. Depending on the location of plants the discharge occurs either in rivers and lakes or in agricultural and forest lands. The 80% of treated sludge from MTWPs is disposed to landfills, including 10% curtilage, 6% reuse for agriculture and 4% forestry. From statistic surveys the production of dry sludge in Greece reaches the 43 g DS/capita/day. As it is obvious, landfilling is the most dominant method for sludge treatment as well. There is no specific legislation in order for reuse or further treatment to be promoted.

The sludge produced from the anaerobical stabilization MWTPs, consists more than 80% of the total sludge. As studies have indicated this amount of sludge could be reused for agricultural activities. Also through anaerobic digestion, biogas could be produced [62] [63] [64] [65].

But this situation resulted in Greece facing European Union Court of Justice due to the failure of ensuring that municipal wastewaters are properly treated and complying with Directives. In European Union, all Member States must conform to the Municipal Wastewater Treatment Directive (91/271/EEC), which requires sufficient collection and treatment systems for municipal sewage. In 2010, our country received the first warning about this case concerning areas with population range from 2,000 to 15,000. From 1991, when the legislation was introduced to 2000 member states should ensure adequate urban wastewater treatment from large towns and until 2005

from smaller ones. Greece did not accomplish to present complete reports as eight areas (Prosotsani, Doxato, Eleftheroupoli, Galatista and VagiaPolichronou, Chanioti and Desfina) were still lacking of desirable treatment facilities. This was considered by the Commision as a failure [66] [67].

2.4 Energy from Waste in Europe

Europe meets great development in the field of Waste-to-Energy (WtE) or Energy-from-Waste (EfW) technology. In 2012 as **Figure 10** from the CEWEP indicates, about 460 WtE facilities were operating in Europe, while this number reached the 520 plants in the mid of 2013. 95 million tons of MSW and commercial waste are treated in these facilities annually. Over the last five years, the capacity of European WtE grew by 24% annually, with 73 new facilities entering in the market [61] [68].

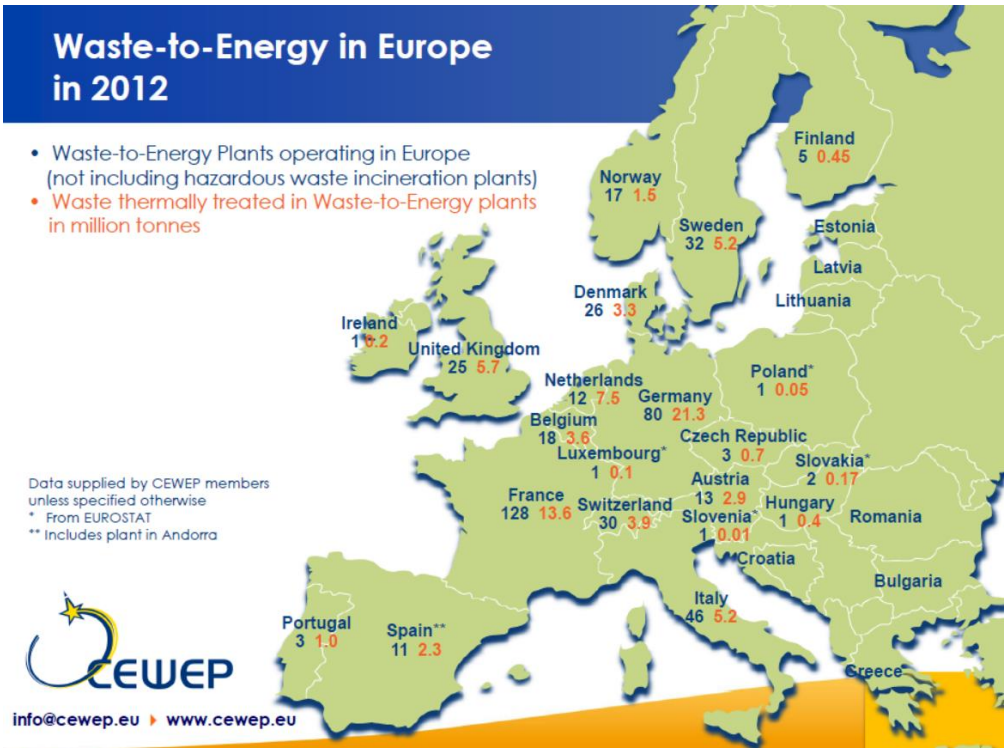


Figure 10. Waste to Energy Plants in Europe in 2012 (CEWEP).

Trough Waste to Energy technologies, energy is recovered from the conversion of waste into steam, heat, electricity or fuel. The processes that WtE includes are incineration/combustion, gasification, pyrolysis, anaerobic digestion and landfills gas recovery [61] [69] [70]. The most common and dominant WtE technology is

incineration. Thermal technologies of gasification and pyrolysis are not so popular and wide used and are still in initial stages of evolution [23] [69] [70].

Waste incineration plants exploit the energy content of MSW to produce electricity, steam, heating and fuels while both reducing waste's volume by 90%. The aim of technology is to reduce the biodegradable content of municipal waste, eliminate the production of methane, reduce dependence on energy imports, enhance economy and secure the energy supply by replacing the use of fossil fuels from conventional power plants with waste as alternative fuel [61] [69] [70].

An example of the way that this technology contributes in all these aims is Netherland. Regarding the CEWEP Country Report for Netherland for the period 2012-2013, the country produced totally 9.5 million tons of MSW, from which the 50% was recycled, the 23% was incinerated and less than 0.5% was landfilled. Netherlands occupies 12 WtE units and 6 dedicated RDF units that treated thermally 7.48 million tons of waste in 2013 and produced 4.67TWh/year. The country exported 3.95TWh of electricity and 2.02TWh of heat in the same year period. Due to the flue gas cleaning system and the bottom ash system of this technology the total residues production was 1.7 million tons from which the 100% was recycled and reused in road construction, cement production, construction block fabrication, and landfill [61] [71].

Table 6 demonstrates reported results of Eurostat in order to comprehend the scale of discrepancy between Europe and Greece regarding waste management and energy recovery potential. It is noticeable that the development of an integrated municipal waste management in Europe reduced the volume of wastes by approximately 7% from 2005 to 2013, while the waste disposal was reduced by 34%, and the total incineration including energy recovery was increased by 25.5% during the same period. However the adverse situation was observed in our country, where the waste generation was increased by 17%, the waste disposal by 7%, while no exploiting for energy recovery occurred [45].

Table 6. Waste Management in EU and Greece.

Waste generated (kg/capita)									
	2005	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
European Union	516	522	524	521	511	504	498	489	481
Greece	437	443	448	454	461	531	503	506	510
Landfill / disposal (kg/capita)									
European Union	221	220	214	200	193	184	168	156	146
Greece	387	386	358	374	374	440	412	408	412
Total waste treatment (kg/capita)									
European Union	483	495	502	501	497	491	485	476	471
Greece	439	443	448	454	461	531	503	506	510
Total incineration (including energy recovery) (kg/capita)									
European Union	98	104	105	110	112	114	120	118	123
Greece	0	0	0	0	0	0	0	0	0

According to CEWEP a WtE plant saves CO_2 between 100 and 450 kg CO_2 eq /ton of waste processed, depending on the waste composition, the amount of heat and electricity supplied and the country energy substitution mix. In case of WtE replacing landfilling, there would be further savings of 200-800 kg CO_2/ton wastes. The environmental effect of the WtE plants is the reduction of carbon emissions. Although the emission of MSW incineration is 1,671 kg CO_2/MWh, which is greater than this of coal at 1,020 kg of CO_2/MWh, less than 50% of those carbon emissions contribute to climate change. In fact only 835.5 kg CO_2/MWh considered to be emitted and correspond to emissions from biogenic sources [72].

3. Renewable Biomass Energy

Article 3 of the RES Directive (2009/28/EC), of the European Parliament and the Council on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, contains the definition of biomass. The definition defines: *"Biomass means the biodegradable fraction of products, waste and residues from biological origin from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste; it includes bio-liquids and biofuels."* This definition is supplemented by two new definitions, also taken from the RES-D: *"bio-liquids means liquid fuel for energy purposes other than for trans-port, including electricity and heating and cooling, produced from biomass."* and *"'biofuels means liquid or gaseous fuel for transport produced from biomass"*.

Biomass is a term used to describe all organic matter produced by photosynthesis, existing on the earth's surface. It includes all water- and land-based vegetation and trees, and all waste biomass such as municipal solid waste (MSW), municipal biosolids (sewage), and animal wastes (manures), forestry and agricultural residues, and certain types of industrial wastes. The world's energy markets have relied heavily on fossil fuels. Biomass is the only alternative natural energy-containing carbon resource with such large quantity that can be used as a substitute for fossil fuels [73].

Energy from biomass has always been a significant factor in the evolutionary root of human. For many decades biomass was, and still is for many countries, the main energy source of the basic domestic needs such as cooking, heating water and air, mainly in the form of wood. Today, biomass is considered to correspond to the 10-14% of the world's energy production [74] [75].

Although there are more developed technologies in order to extract biomass and convert it into useful energy, the intrusion of fossil fuels with their high economic advantages and energy efficiencies caused the reduction of biomass energy usage. But the eventual depletion of fossil fuels coupled with their severe impacts on the environment, brought biomass back to the fore [73].

Biomass, in comparison with fossil fuels, is considered to be a totally renewable source of energy as it can be replenished in a relatively short period of time [74]. Moreover, the burning of biomass, due to its life cycle and origins, does not contribute to the greenhouse effect –zero balance CO_2– as the amount of CO_2 released during this process has already been captured from the atmosphere to generate biomass as presented in **Figure 11**. Biomass, consists mainly of carbohydrates, and is produced by the reaction of CO_2 in air, water and sunlight, through the photosynthesis process. The energy stored in biomass can be extracted through a variety of conversion technologies that cause the oxidization of its components in order to produce CO_2 and H_2O. The process is cyclical, as the CO_2 is then available to produce new biomass [75].

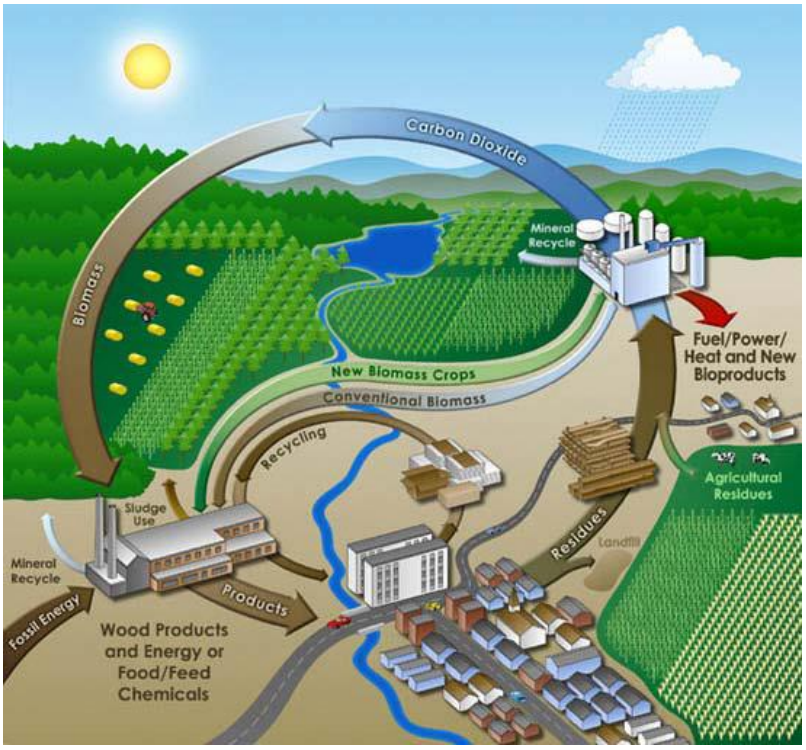


Figure 11. Life Cycle of Biomass.

The usage of biomass for energy production also contributes to in avoiding the emission of Sulphur dioxide (SO_2) generated during the combustion of fossil fuels that contributes to the phenomenon of "acid rain". The Sulphur content of biomass is practically negligible [73].

The reduction of energy dependency from third countries, by decreasing fuel imports of fuel, with a corresponding foreign exchange savings, is also one of the advantages

of the exploitation of energy from biomass. Biomass, finally, contributes to regional development by securing and avoiding de-population of rural areas in border and other agricultural areas [75].

Today, the use of biomass to recover energy is extremely widespread in both OPEC and non-OPEC countries. Developing countries produce about one third of their energy from biomass. About 2.5 billion people depend essentially on biomass to meet their needs for heating, lighting and cooking [73] [74] [76].

Furthermore, biomass covers a significant part of the energy needs in developed countries as well. Hence, in U.S. biomass covers about 4% of its primary energy needs, in Sweden 13% and in Canada 7-8% of the final energy demands [76].

3.1 Biomass to Energy Conversion Technologies

The energy that derives from the specialized treatment of biomass resources is the so called “bioenergy”. Bioenergy includes all forms of fuel produced by the conversion of biomass, liquid, solid and gaseous. Liquid fuels allow their direct use in transportation means and also in engines and turbines for electricity generation. On the other hand, solid and gaseous fuels can be used in power plants for electricity production [41] [42].

Renewable biomass sources are divided in three categories, primary, secondary and tertiary sources. Primary biomass sources include the woody source of biomass, (lignocelluloses) produced by photosynthesis and taken directly from the land, like forest, agricultural and landscape residues, waste wood residues, energy wood plantations, industrial wood residues and residues from food and more specifically the biodegradable fraction of municipal wastes. Secondary biomass sources is the non-woody biomass, oil, sugar and starch, such as residues from the primary biomass sources process, agricultural energy plants, straw and other harvesting agricultural residues, landscape residues food industry residues etc. Tertiary biomass resources are post-consumer residue streams including animal fats and greases, farm slurry, slaughter waste, organic waste from households and industry, used vegetable oils, packaging wastes, construction and demolition debris [41] [42] [77].

Biofuels are divided into different categories as well, according to the feedstock they are coming from. Thus, we can distinguish three basic generations of biofuels. First generation biofuels are produced from the available raw material such as oil seeds, cereal grains, agroindustry and other organic residues, energy corps, agricultural and forest residues. This category of biofuels includes biodiesel, bioethanol, biogas and pellets. Second generation biofuels derive from the use of the primary material that cannot be used as food. These materials could be waste and residues from vegetable and animal fats, cellulosic plants that are not used as food, agroindustry and other organic waste and residues and municipal waste. The products resulting from this category are biodiesel, bioethanol, bio-methanol, bio-hydrogen, biogas, syngas, synthetic diesel and synthetic kerosene. The production of the third generation biofuels is based on microalgae. The technics for this conversion are still in initial stages but with great expectations for the future [41] [42] [77] [78].

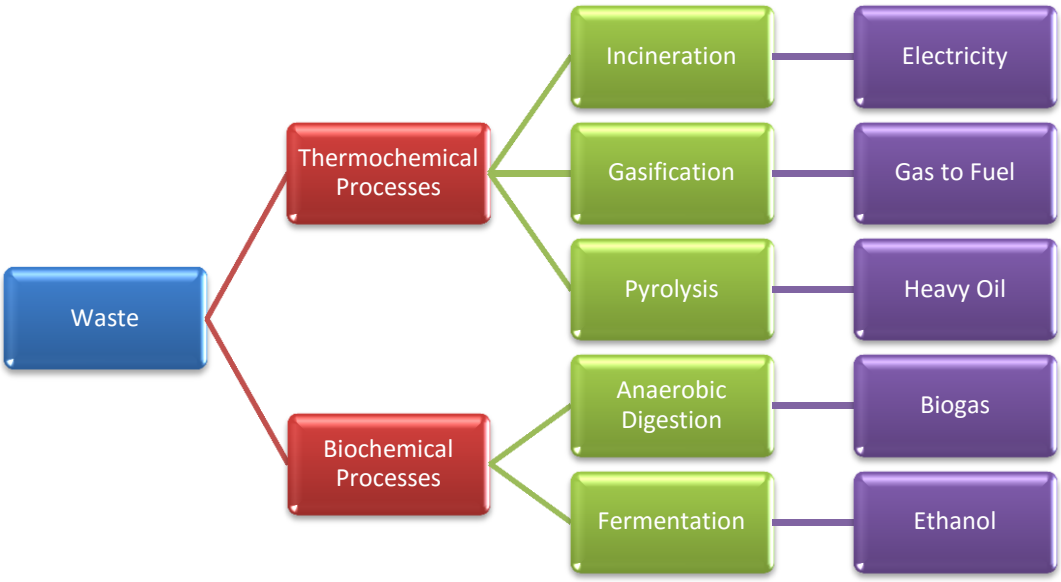


Figure 12. Biomass conversion processes.

This thesis aims to examine the energy recovery from the second generation biofuels and mainly from municipal waste.

Biomass can be used to meet energy needs such as heating, cooling, electricity, etc. either by direct combustion, or by transformation into gases, liquids and/or fossil fuels through thermochemical or biochemical processes as **Figure 12** illustrates [41] [42] [79]. The selection of the biomass conversion technology, in each case, depends on

various factors such as the form of energy that is required, the environmental issues, the type and quantity of feedstock that is available and economic factors [42].

3.1.1 Thermochemical Conversion

The thermochemical conversion of biomass occurs in high rates and high temperatures usually over 800°C, by means of heat. This process is more suitable for low moisture lignocellulosic biomass such as herbaceous and woody biomass, energy cultivation or wastes. Heat, electricity, intermediate gaseous or liquid fuels are the main products of thermochemical conversion [41].

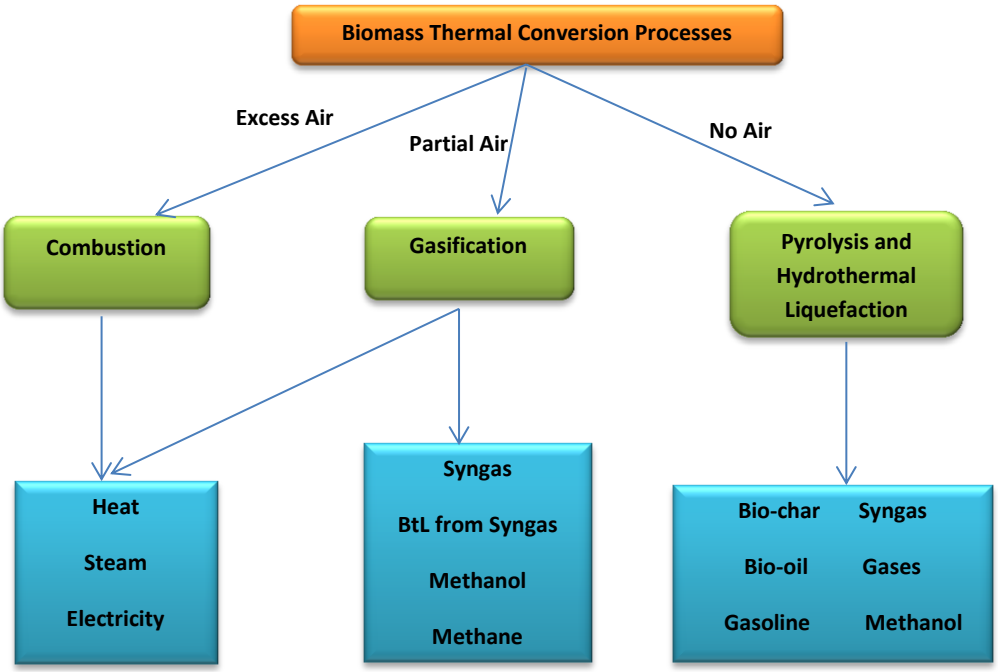


Figure 13. Thermochemical conversion routes.

The three principal methods of thermochemical conversion are combustion, gasification and pyrolysis which occur in excess air, partial air and absence of air respectively. **Figure 13** illustrates these processes, with the intermediate and final products of each thermochemical technology [41] [42].

3.1.1.1 Biomass Combustion

Combustion might be the most common and simplest technology in order to extract energy -both heat and electricity- from biomass. It is the thermal conversion of biomass using excess air, where the components of biomass are converted to their respective oxidized form. There is a high variation concerning the feedstock that should be used in biomass combustion. It is a process that can includes many types of biomass fuels such as wood, agricultural residues, wood pulping liquor, municipal solid waste (MSW) and refuse-derived fuel (RDF).

During combustion of biomass warm gases (steam) are produced at high temperatures of around 800°C to 1000 °C. This process is preferred mostly for raw materials with a moisture content that does not exceed the 50%, unless they are pre-dried. The scale of combustion facilities ranges from household (very small) to industrial 100-3000MW, which is another reason for its wide dissemination. The relative efficiency of biomass combustion to electricity in power plants, which is a combination of the efficiencies of the Rankine cycle, the boiler and the turbine, ranges from 20% to 40% and it is higher in case of co-combustion of biomass in coal-fired power plants [74].

The incoming biomass fuel is burned directly in a boiler to turn water into steam, which contains 60 to 85% of the potential energy in the biomass fuel. The steam produced, turns a steam turbine which drives a generator which in its turn produces electricity and heat so to be used in homes, businesses, institutions and industries. Afterwards, the steam is condensed trough wet cooling or once-through cooling and it returns back to the boiler. Residues of biomass combustion consist of bottom ash and fly ash from the combustion chamber as well as residue from flue gas cleaning system [41] [79]. An example of a typical biomass combustion method is demonstrated in **Figure 14**.

The main products of biomass combustion are carbon dioxide (CO_2) and water vapor (H_2O), though tars, smoke and alkaline ash particles are produced as well. Thus, a proper and environmentally acceptable biomass system with diminished emissions is required. In order for a proper and sufficient combustion to occur three requirements must be fulfilled. These three requirements are (a) high temperatures for ignition, (b)

sufficient turbulence for the proper mixture of oxygen with all components of biomass fuels and finally (c) plenty of time in order for a complete oxidization reaction to be succeeded.

The most common type of biomass boiler is the grate furnace which is based on a grate with a bed of fuel that is mixed with a controlled amount of combustion air, which usually enters from beneath the grate. Biomass fuel enters from the one end of the grate and it is burned in the fuel bed which moves progressively down the grate, in most cases with mechanical assistance or gravity. The fuel bed leads to the ends of the grate where there is an ash removal system. In general the whole combustion process consists of four main steps:

1) The initial fuel drying, where the biomass fuel is heated up to $100^{o}C$ in order to remove the water

2) Pyrolysis or De-volatilization, where the chemical decomposition of biomass occurs in anaerobic condition in order for the volatile gasses such as HC, CO, CO_2, H_2, CH_4 and char to be removed.

3) Gasification or Flame Combustion, where the emitted gasses from pyrolysis are mixed with atmospheric air and burned in high temperatures in order to produce CO_2 and H_2O.

4) Combustion, where the remaining from the previous phases matter, mainly char, is burned in lower temperatures and produces ash.

During each step of combustion the amount of biomass fuel decreases significantly to finally reach even 90% reduction of the initial amount that entered into the system.

The main drawback of this technology is that there is creation of ash slagging that, inevitably, causes a decrease in efficiency and increases costs. Thus, the range of materials that can be used in direct combustion is relatively limited.

The advantage of grate furnace is that it is has high tolerance in moisture content and particle size of biomass, it is less sensitive to slagging and it can comply with a high variation of different fuels. It is considered to be a very efficient system recovering 65-90% of the energy content in the biomass fuel with a capacity range from 100kW to 50MW. However, all energy contained in biomass fuels is not converted to useful

energy; there is also an amount of heat losses to the exiting flue gases, the ash leaving the boiler as well as heat losses during the evaporation of biomass' water. Additionally, radiation heat losses and incomplete combustion of char and gases is another reason that reduces the efficiency of the system. Hence, the total efficiency of energy recovery depends on the Rankine, boiler and turbine efficiencies which range between 30-45% , 75-85% and 5-30%, respectively [41] [80] [81].

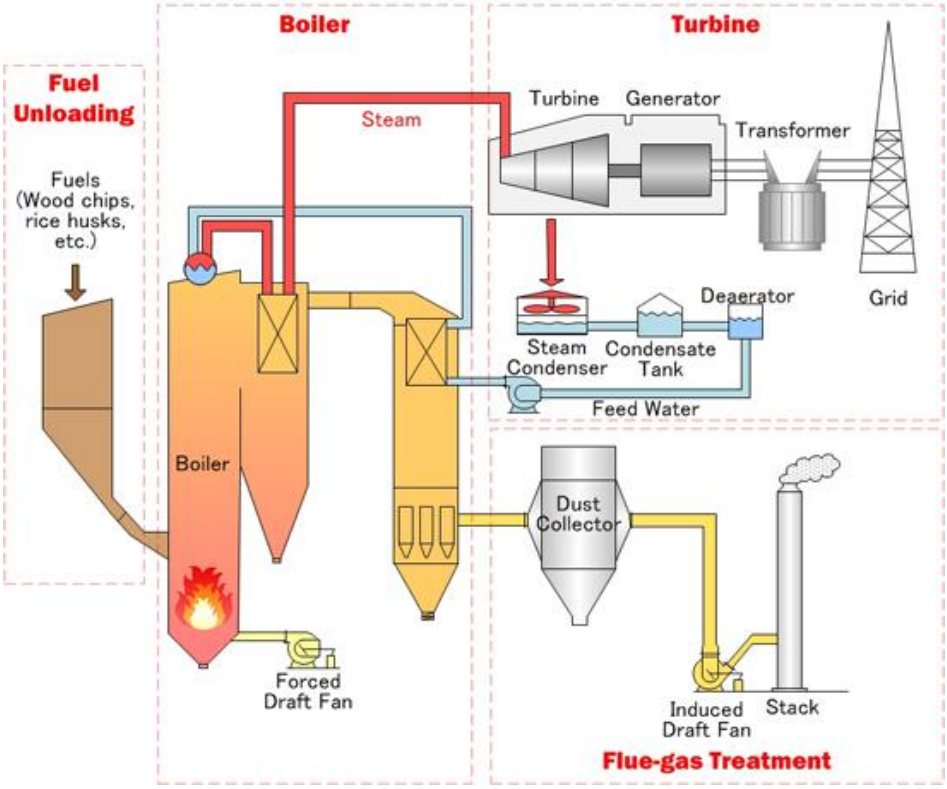


Figure 14. Example of Direct Combustion Power Generation Method.

In commercial biomass combustion systems, used worldwide, there is a variety of direct combustion technologies which are used and which are formed primarily according to the local availability of raw materials. In general, there is no particular restriction concerning the raw material. Exclusive biomass combustion plants can burn a wide range of fuels, including wastes.

Combustion of solid wastes is the most common and worldwide method of waste treatment with numerous facilities around the world, a great number of which exceeds the capacity of 1.000.000 tons/year. In combustion, the components of solid wastes undergo in high temperatures with the presence of flame and air in order to be

converted to heir oxidized form. The municipal solid waste combustion systems can operate with two different types of fuels.

1. The commingled solid waste, mass-fired, facilities, where there is no requirement for any pretreatment of the waste
2. Facilities that operate with treated RDF, refuse-derived fuel, as fuel.

Primers are the most commonly used combustion systems. Their great advantage is that it is more convenient, as wastes are imported with no treatment in the combustion facility. In any case supervising of the incoming materials is prerequisite.

The latter category, the RDF units in comparison with the mass-fired units, comply more efficiently with the energy recovery and distribution network as the RDF has higher heating value and much smaller fluctuations in energy content. Moreover, these facilities are of smaller scale and their control is simpler. Finally, the removal of metals, plastics, PVC etc. assists the production of less dangerous waste gases. The RDF units are comprehensively fewer than the mass-fired units, as they require a supplementary unit for RDF production [41] [48] [82] [83] [84].

The whole combustion process takes place in special incinerators whose capacities can vary from 8 to 25Mg/h. The most widespread types of incinerators are:

- Fixed-bed Combustion

Grate furnaces and underfeed stokers are included in these systems. The biomass processing phases, drying, gasification and charcoal combustion take place on a fixed bed though which the air passes. Secondary air is introduced in a separate combustion zone and used in order to burn the combustible gases. Grate furnaces have high flexibility concerning moisture and ash content and particle size as well as low sensitivity to slagging. They are susceptible in mixing of different wood fuels. However, the different combustion behavior, the low moisture content and the low ash melting point of some wood types, such as straw, cereals and grasses, cause malfunctions. In most cases the capacity of fixed- bed combustion system reach the 20 MW_{th}. On the other hand, underfeed stokers are a lower cost technology applied mainly in smaller or medium scale facilities with capacities around 6 MW_{th}. This technology is more suitable for lower moisture and ash content biomass and smaller particle sizes [41] [85].

- Fluidized bed Combustion

In fluidized bed systems, air is introduced from beneath and burns biomass fuels in a self-mixing suspension of gas and solid bed material, mostly silica sand and dolomite. Fluidized bed combustors have high flexibility concerning moisture and ash content and particle size as well. The high turbulence of the system provides a high heat transfer capacity, thus, complete combustion with low recess oxygen occurs and increases combustion efficiency whilst it decreases flue gas flow. However, they are not able to comply with ash slagging. Fluidized bed combustion is more suitable for large scale facilities, usually more than 30 MW_{th} capacities, as they have high operational costs [41] [85].

- Dust Combustion/ Pulverized Fuel Combustion

Dust combustion or pulverized fuel combustion technology is more suitable for low moisture and small particle size biomass fuels in the form of dust or powder. In these combustors air is introduces along with the fuel into the chamber. Secondary air is also introduced in order to burn the gases. The combustion takes place under medium excess oxygen conditions increasing the efficiency. However, there is a need of a supplementary burner in order to start up the process. This combustion technology is addressed to facilities with 2 MW to 8 MW capacities [41] [85].

3.1.1.2 Biomass Gasification

Gasification is the thermal conversion process of partial combustion of biomass, where the organic fraction of the biomass fuel is converted into a mixture of gas fuel, the also called syngas, a synthetic gas consisted of CO, CO_2, H_2, H_2O and CH_4, under partial air (oxygen) and high temperatures, greater than 800^oC. The produced gas has a low calorific value (CV), lower than 10 MJ/Nm^3, usually around 4-6 MJ/Nm^3. The produced combustible gas can be used as a fuel in boilers, internal combustion engines or gas turbines. Gasification is particularly suitable to treat industrial wastes but there are some problems with municipal [41] [86] [87].

The gasification method is a recent entry in the waste management treatment with the Integrated Gasification Combine Cycle (IGCC) meeting high potentiality in the near future. The advantage of IGCC is that it combines Brayton and Rankine cycle, with the improved final efficiencies. In the Brayton cycle the typical exit temperature of

the gas (400-600°C) is high enough in order to generate steam, which can produce electricity through a Rankine cycle and run a combined cycle which increases the efficiencies that range between 30% and 40% [41] [86] [87].

In comparison with combustion, gasification of biomass fuels is an exothermic process with partial oxidization and it has higher efficiencies due to the IGCC. The energy needed is supplied mainly externally but also internally through the combustion of part of the inserting biomass fuel. Regarding the oxygen supply, in case of gasification reaches the 1.5-1.8 kg air/kg biomass, whilst in combustion this is around 7 kg air/ kg biomass. It has also the ability to produce chemicals and liquid hydrocarbons with lower emissions of NO_x (sulfur) and particulates, while it eliminates dioxins and furans. However, there are some restrictions that must be fulfilled in this process, aiming high efficiencies of gasification biomass conversion. It is a process more suitable for low moisture and ash content, less than 15% and 5%, respectively, as high moisture and ash reduce the Heating Value (HV) of the fuel, create slagging problems and decrease the total efficiency of the process. Additionally, medium size of particles is required to secure proper movement of the feed and high pressures [41] [86] [87].

The whole process of gasification is divided in four main phases which are the following:

1) Heating and Drying, where the excess moisture content is removed in order to reach to the limits of 10-15%.
2) Pyrolysis, which occurs under 280-500^{o}C of temperature for charcoal and tar to be removed.
3) Partial Combustion/Oxidization of gases, steam and charcoal which are converted into CO_2 and H_2O, under high temperature (1500^{o}C) and partial air conditions, by a gasifying agent, usually oxygen.
4) Gasification/Reduction of charcoal from the previous phase and production of CO, CH_4 and H_2 [41] [86] [87].

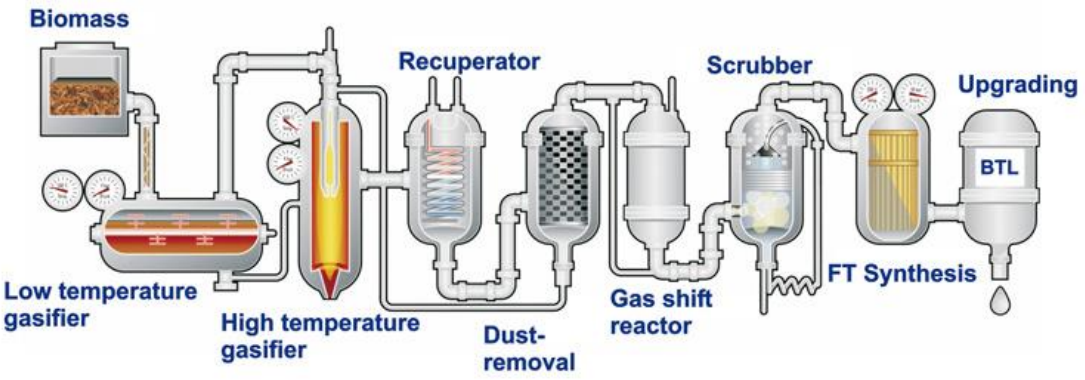


Figure 15. Biomass Gasification Process.

Biomass gasifiers are classified, depending on the type of gasifying agent, operational pressure, reactor type and heat requirements. The gasifying agents are:

1. Oxygen/air
2. Steam and
3. Carbon dioxide

In case of an oxidant gasification agent, partial combustion/oxidization of biomass for heat supply of gasification occurs and the temperature remains up (direct gasification). On the contrary, in case of steam as gasifying agent indirect gasification occurs, thus, external heat supply for the gasification is required. In the second case, the produced gas (syngas) has a heating value that ranges between 15 and 20 MJ/Nm^3 and which is higher than this in direct gasification [41] [87] [88].

There are three types of reactors where the conversion occurs:

- Fixed-bed/Moving bed reactors

In fixed-bed reactors, biomass moves slow through the reactor. This type of reactor is divided in two further types as presented in **Figure 16**: (a) the updraft or countercurrent and (b) the downdraft or co-current. In the former, biomass is introduced from the top and the produced gases also pass upwards, whilst he gasifying agent enters from the bottom of the reactor. In the pyrolysis zone biomass is converted into condensable and non-condensable gases and charcoal. Part of char is burned through combustion and the heat produced is used to the whole process. In the latter, biomass is also introduced from the top, whereas the gasifying agents is

injected from the bottom, from one side and passes through the pyrolysis zone where it is mixed with pyrolysis products, gases and solids (charcoal and tar) and which move downwards. A part of gases produced from pyrolysis are burned through the gasification zone and provides with heat energy for the operation of all phases. Downdraft reactors have an overall lower energy efficiency, lower gas and tar content and higher particulate content than the updraft reactors [41] [87] [88].

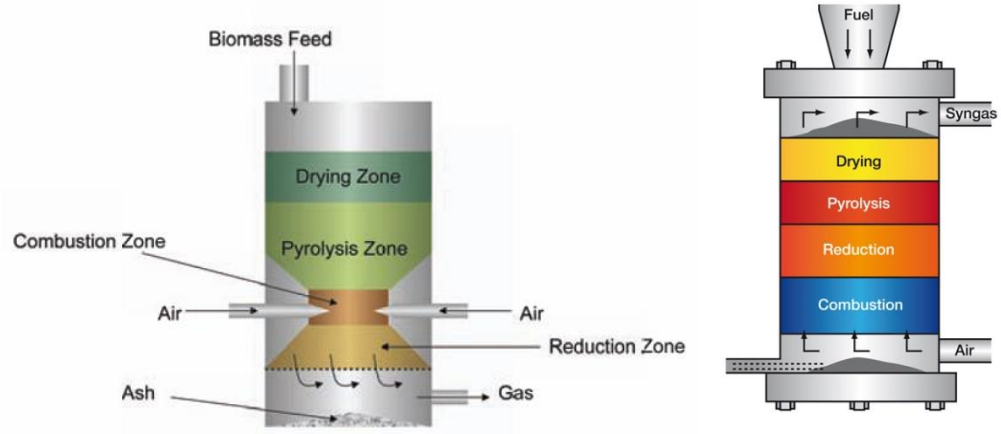


Figure 16. Fixed bed reactors (a) downdraft (b) updraft

- Fluidized bed reactors

There are two main types of fluidized bed, the bubbling and the circulating fluidized bed. In general, in fluidized bed reactors the biomass fuel is inserted from the top, whilst the gasifying agent, in the form of fluidized gas, is introduced from the bottom in a continuous pace and exits from the top. The phases of drying and pyrolysis occur when the incoming fuels are mixed with the hot solids on the grate and charcoal and gases are produced. However, this continuous mixing of fuels prohibits the acceleration of a complete conversion of char and high efficiencies. The advantage is that the constant mixture of solids offers the stabilization of temperature in specific ranges between 800^{o}C and 1000^{o}C which prevents slagging. Nevertheless, this mixture of already gasified and partially gasified particles results in the production of partially gasified char which in its turn causes losses in the reactor. In case of bubbling fluidized bed reactors oxygen is inserted in the form of bubbles and heat is produced by the partial combustion of volatile matter and char. The problem of this reactor is the low dissemination of oxygen from bubble to the emulsion phase which leads to the combustion during the fluidized phase causing the reduction of efficiency of gasification. Circulating fluidized bed reactors, also heated by the partial

combustion of volatile matter and char, but in this case there is no oxygen bubbles which prohibits the gas to pass through the grate. In this type of reactor a part of particles that leaves the reactor returns back through the separation in the cyclone. Both fluidized reactors are characterized by short residence time, high productivity, uniform temperature distribution, low char and tar generation, reduced slagging and they are suitable for various fuels such as biomass, MSW and lignite. Still, bubbling fluidized bed reactors have higher efficient heat exchange than the circulating type [41] [87] [88].

- Entrained bed reactors

This type of bed reactors is more suitable for integrated gasification combined cycle (IGCC) facilities. The fuel in the form of powder is inserted in the reactor along with the gasifying agent. Heat produced by the reaction of oxygen with the volatile matter and char resulting high temperatures, around 1400^{o}C, preventing slagging, destroying tars and oils, providing high conversion of carbon and high efficiencies [87].

- Twin fluidized bed reactors

Twin fluidized bed reactors include two types of reactors. The first one undertakes the pyrolysis phase and it is heated by the combustion of the sand and hot particles from the second reactor which also burns the char produced from the former. This separation of the two phases leads to the production of syngas with high BTU content due to the low nitrogen and carbon dioxide portion [41] [87] [88].

For a proper and efficient gasification process, homogeneous carbon-based materials are required. MSW as a biomass fuel is a mixture of organic and inorganic matter consisted of solid and liquid components which defines it as heterogeneous. As a consequence a thorough and careful study for the power plants construction is required. The high investment costs, the high complexity of gasification method, as well as the fact that the majority of MSW are not homogeneous carbon-based materials in order to be treated in the gasification process, thus this method will not be analyzed further in the thesis [92].

3.1.1.3 Biomass Pyrolysis

Biomass pyrolysis is the thermal decomposition of biomass to liquid, solid and gaseous fractions, in the absence of air, mainly oxygen and under relatively high

temperatures of 500°C to 800°C, but lower than in the gasification process. The basic products generated from this process are bio-chat, bio-oil and gases such as CH_4, H_2, CO, CO_2. The yield of conversion process as well as the amount of the produced materials depends on the method of pyrolysis, the type of biomass fuel and the reaction parameters. Due to the various components of biomass, cellulose, hemicellulos, lignin and organics, there are different pyrolysis processes for each one. For instance, lignin is decomposed in a slower pace under a wide range of temperatures, whilst cellulose and hemicellulose are decomposed faster in a limited range of temperatures. Thus, the whole process is divided in two stages. In the first one, a slow pyrolysis takes place. In this stage biomass is heated and the fixed carbon component result in char generation. In fast pyrolysis, biomass is heated rapidly under high temperatures, of around 450°C to 500°C, low resident time, less than 1 to 5 seconds and in the absence of air, generating vapors, aerosols and charcoals. In this stage the volatile portion of the organic matter is converted to produce bio-oil and gases [41] [88] [89]. The use fast pyrolysis provides the ability to convert biomass to bio-crude with an efficiency of 75-80%. Fast biomass pyrolysis is used in order to augment either liquid or gas production [41] [42].

Pyrolysis is the thermal conversion of biomass to mainly bio-oil and not electricity. Bio-crude is commonly used as fuel in engine and turbines. In general, pyrolysis and gasification are considered to be two alternative methods to combustion in waste to energy recovery. The generation of gases and liquids from waste conversion are used in later incineration processes, such as boilers or gas engines.

Despite the high efficiency of bio-oil production, it meets some disadvantages as an alternative transportation fuel, such as the high oxygen and water content which results in low heating values and thermal stability of the fuel. Additionally, bio-crude is low quality oil, due to the oxygen content and it is not bendable with conventional fossil fuels [41] [88]. These difficulties can be overcome through bio-oil upgrading, by decreasing the oxygen content and through removing alkalis, by hydrogenation and catalytic cracking of it [41] [42].

3.1.2 Biochemical Conversion

In biochemical conversion, biomass decomposition to its molecules occurs. This degradation of biomass takes place through biochemical reaction with the use of biocatalysts, such as bacteria, enzymes or micro-organisms in addition to heat and other chemicals. This biochemical breakdown of the carbohydrate fraction of biomass, meaning the hemicellulose and cellulose, leads to the generation of gaseous or liquid fuels, such as biogas or bioethanol.

Biochemical decomposition of biomass is a slower method of biomass conversion than thermochemical and also takes place under lower temperatures. In comparison with thermochemical, biochemical conversion is more suitable to high moisture biomass such as municipal solid waste, algae etc. The most widely distinguished biochemical technologies are anaerobic digestion to biogas and fermentation to ethanol**.**

In general the whole biochemical process can be divided into seven steps as demonstrated in **Figure 17**. After the feedstock supply of biomass fuel, it must undergo a pretreatment process where it is heated, along with steam and acid, in order to weaken the strong bonds between its cells and set the next step of hydrolysis of cellulose and hemicellulose easier. In hydrolysis, enzymes or other catalysts are injected to separate the sugars from cellulose and hemicellulose. Then the biochemical conversion takes place, either anaerobic digestion or fermentation, depending mostly on the feedstock origination. Afterwards, the products are separated from water, solvents, and the residual solids and distributed blending units or refining facilities. The solids remaining from the previous processes, mostly lignin residue, are combusted to produce heat and power [41] [80] [90] [91] [92].

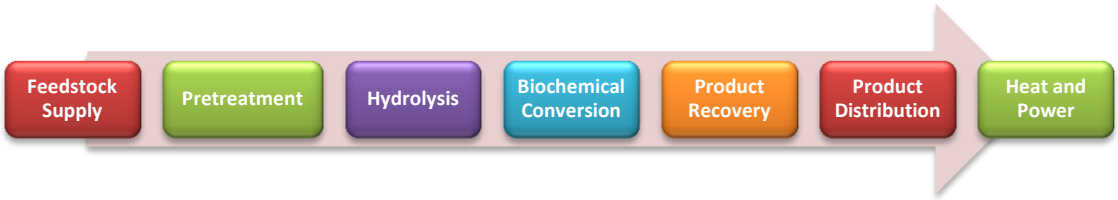


Figure 17. Phases of biochemical process.

Biochemical is considered to be a non-pollutant method of biomass conversion and also it is characterized by low energy consumption. Mostly biogas, ethyl alcohol, compost and protein production have met high development in the last decades. Biochemical conversion of biomass is the most environmentally sustainable alternative for fuel and energy production as well as for the reduction of CO_2 amount in the atmosphere. Biomass is an abundant resource of carbon and it can act as a sustainable substitute for conventional fossil fuels [92].

3.1.2.1 Anaerobic Digestion

Anaerobic digestion is the biochemical conversion of the organic matter of biomass to methane via chemical reactions of microorganisms under a non-oxygenic environment. Through this process bacterium decomposes the carbon in organic matter generating biogas, liquid digestate and solid fiber digestate. The main components in produced biogas are methane (CH_4) and carbon dioxide (CO_2) with a portion of 60-65% and 30-35%, respectively. Ammonia, hydrogen and hydrogen sulfide can also be found in biogas but in lesser amount. Liquid digestate consists of mostly valuable nutrient nitrogen and small quantities of phosphorus and potassium and it can be used as fertilizer, whilst solid fiber digestate contains, mainly, phosphorous and as compost it can be used as soil conditioner.

As it has already been mentioned in the previous chapter, anaerobic digestion is the most common method to organic waste treatment. The combination of waste treatment and energy production via anaerobic digestion met development the last decades and constitutes a significant part in the integrated municipal waste treatment for many European countries as it can process both wet and dry biomass. Feedstock for anaerobic digestion include manure, municipal solid wastes and organic waste from households, wastewater sludge, harvest surplus, vegetable oil residues and specific energy corps.

For anaerobic digestion the biochemical process, explained above, after hydrolysis, is divided in four more steps. The first one is acidogenesis during which acetate (CH_3COO-), carbon dioxide, volatile fatty acids and hydrogen are produced. The volatile fatty acids produced are decomposed in the next step, acetogenesis, where acetate and hydrogen along with carbon dioxide are composed. Methanogenesis is the

final step of this process and concerns the conversion of acetate and hydrogen to methane and carbon dioxide [41] [80] [88] [91] [92].

The exploitation of the generated biogas provides energy with high efficiency and environmentally sustainable due to the low emission of pollutants. Additionally it does not need high amounts of energy although it is not an exothermic reaction. The amounts of heat needed to maintain the high temperatures and produce sufficient energy is obtained by the combustion of biogas that is produced [88] [93]. The produced biogas is usually used in Combined Heat and Power (CHP) units. CHP installations produce electricity and heat production, simultaneously, with typical efficiencies of about 33% and 45%, respectively [93] [94] [95]. A typical installation of municipal waste exploitation via anaerobic digestion is presented in **Figure 18**.

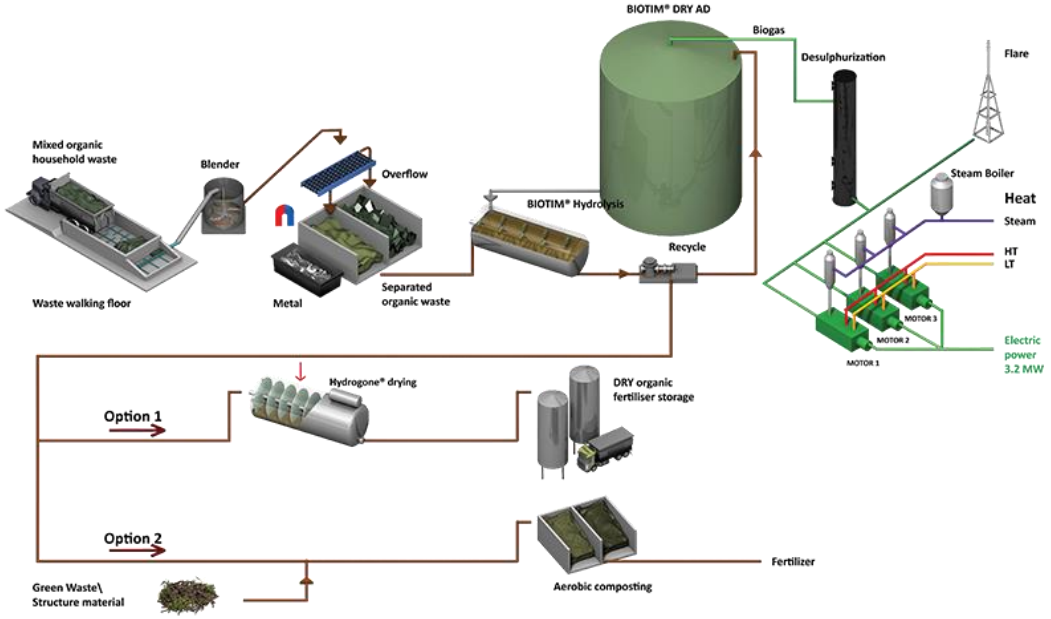


Figure 18. Anaerobic municipal waste conversion facility.

In comparison with combustion, which is the most prevailing technology nowadays, anaerobic digestion has numerous advantages. First of all, it can process both wet and dry biomass which contributes to the efficient municipal solid waste and wastewater treatment, the reduction of waste volume, the water, ground water and soil contamination and the reduction of odors by about 80%. It also limits, significantly, the emission of hazardous pollutants such as volatile organic compounds (VOCs) as almost 99% of volatile compounds undergo a complete oxidization during combustion. In the contrary, during combustion emissions of dioxins and other

pollutants cannot be restricted in such a high level, and so flue gas purification is required. Moreover, biogas can be upgraded to bio-methane, by removing mainly CO_2 and H_2S and other S-containing compounds through scrubbing and it can be injected in any methane use, such as natural gas grid [41] [93] [94] [95].

Regarding MSW, in case that there is a source separation of the biodegradable fraction from the not biodegradable, the anaerobic treatment is achievable. However, in case of not separated MSW, a pre-sorting is required in order to remove the non-biodegradable compounds which are not suitable for this process, such as heavy metals, so to recover high quality sludge. The consequence of this pretreatment is the increase of the increase of the operation costs. As for the methane yield of anaerobic digestion of MSW, it is characterized by a great variation and depends on MSW composition of each region, season and lifestyle. Each type of MSW components has a different methane yield as it is illustrated in **Table 7** [93] [96].

Table 7. Methane yield, obtained through anaerobic digestion of municipal solid waste (MSW) types.

Type of MSW	Methane yield (m^3/kg ODS)
Mechanically sorted (fresh)	0.22
Mechanically sorted (dried)	0.22
Hand sorted	0.21
Grass	0.21
Leaves	0.12
Branches	0.13
Mixed yard waste	0.14
Office paper	0.37
Corrugated paper	0.28
Printed newspaper	0.10

As for municipal wastewaters (MWW), the disposal of huge amounts of sludge resulting from current sewage treatment plants, does not contribute to the objective of reducing the amount of waste disposal. It also does not represent a sustainable method of treatment and it has high operating costs which rise up to 50% of operating costs of a sewage treatment plant. Today, typical amounts of this sludge are considered to reach the 60-90 g of Dry Solids (DS)/population equivalent which corresponds to an annual total production of around 10 million tons of dry sludge in Europe. This problem can be constricted efficiently enough via anaerobic digestion, as almost 40%

of the biosolids fraction of sludge can removed before the final disposal. Anaerobic digestion is not only an environmental friendly method of wastewater treatment but it is considered to be a way of reducing the operating costs of wastewater treatment plants as well. As in MSW so in MWW too, the methane yield via anaerobic digestion depends on the composition of sludge. However, this technology has the highest biogas production on an international scale, with a typical average methane yield being around 0.590m^3/kg ODS [41] [93] [94] [95] [96].

In general, anaerobic digestion outweighs the other technologies in environmental, economic and efficiency approaches. In terms of combustion, there is still a significant issue with the emission of pollutant gasses such as dioxins that sets a gas purification system mandatory. As regards pyrolysis and gasification technologies, they are still in pilot phase without great scale of such facilities worldwide. Nonetheless, anaerobic digestion technology needs further development in various fields such as the pre-treatment methods so to enhance the anaerobic bio-degradability of feedstock and the upgrading and purification of the generated biogas [93].

3.1.2.2 Fermentation

Fermentation is the aerobic conversion of biomass sugars to alcohol via chemical reactions of microorganisms, mainly yeast, under oxygenic conditions. The principal product of this process is bioethanol which is the most prominent biofuel. Sugar and starch crops and in general cellulosic feedstock are used in large commercial scale in numerous countries in the world in order to produce bioethanol through fermentation. Today, bioethanol is used as engine fuel, as alternative fuel to gasoline in modified gasoline engines and as fuel mixed with fossil gasoline in conventional vehicles. Additional product of the anaerobic digestion of biomass is high quality compost that can be used as soil improver and the generation of carbon dioxide and water. Nevertheless, it is not considered to be a method for energy regeneration [41] [42] [88].

4. COCO Simulator

The main objective of the thesis is the modelling of an energy production system that uses alternative fuels. Hence, a simulation software is applied, so to design the whole operational process of biomass conversion system. The purpose is build, step by step, the entire biomass conversion process including the environmental conditions, the intermediate and final products of each phase along with their quantities and conversion efficiencies. Furthermore, the simulation process will act as an indicator for the conversion technology that should be used in order to exploit more efficiently the type of available biomass providing optimum energy production. The software used for this purpose, is called COCO (CAPE-OPEN to CAPE-OPEN) simulator. CAPE-OPEN is a product of collaboration of various operating companies, such as Air Liquide, BP, DOW Chemical Company, Shell Global Solutions and others, software suppliers and Universities with the support of EU. It is accurate software with well-established unit operations and high variety of implementations [97] [98].

4.1 The Software and its Components

The COCO (CAPE-OPEN to CAPE-OPEN) simulator software consists of an accumulation of software components aiming to enable modelling of steady state chemical engineering flowsheets. It includes four main constituents which are presented in **Figure 19** [99] [100]. In COCO simulator a graphical representation, called Process Flow Diagram (PFD), is used in order to define the simulated process. It also provides the ability to edit the unit operation parameters defined via the CAPE-OPEN standard, which is a compliant steady-state simulation environment consisting of these sub-models. In essence, it is about a flowsheet modelling environment enabling user to add new unit operations or thermodynamics packages [100] [101].

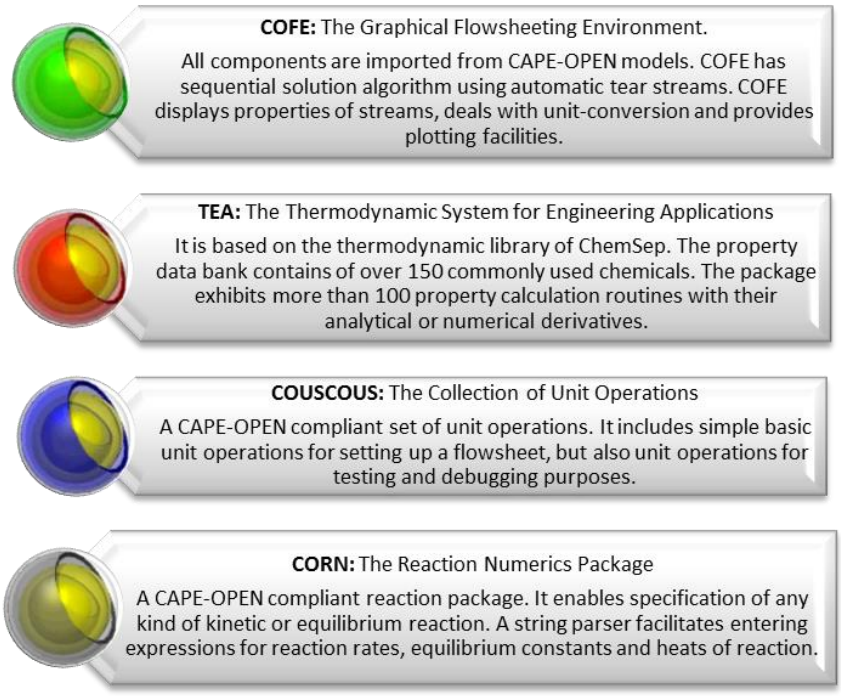


Figure 19. The sub-models components of COCO Simulator.

The CAPE-OPEN sub-models that are usually used are thermodynamic models, unit operation models and a class of models enabling the specification of reactions, such as stoichiometry, reaction rates, heats of reaction, etc. It is a steady state flowsheet simulator including several unit operations linked together by material and energy streams in combination with thermodynamic and physical property models, in order to model complete chemical processes. It is used for designing and operating chemical processes [100] [101] [102].

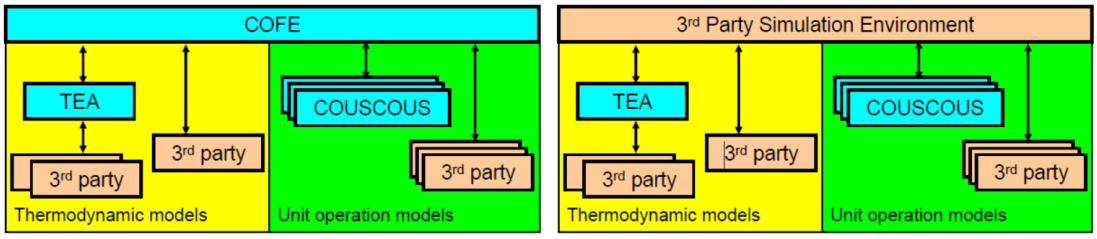


Figure 20. Illiustration of imulation eenvironments with thermodynamic models and unit operations of COCO.

Regarding the setup of COCO, it is totally modelled around CAPE-OPEN and it operates as demonstrated in **Figure 20**. Thus, COFE can be run with TEA which is the COCO's thermodynamics library, or with any third-party CAPE-OPEN compliant

thermodynamic components there is no requirement of built-in sub models or thermodynamics or proprietary interfaces. Furthermore, COFE can be run with COUSCOUS which is the COCO's unit operation models, with any other third-party CAPE-OPEN compliant unit operation models. In similar way TEA and COUSCOUS can be used not only in COFE but in any other third-party CAPE-OPEN compliant simulation environment, as well [97] [103] [104].

4.1.1 COFE: CAPE-OPEN Flowsheeting Environment

COFE features a graphical flowsheet editor, a built-in property calculator, a compact display of stream information and Windows features like graphical printing and print preview, as **Figure 21** displays. COFE also provides the ability to combine flowsheets in a Microsoft Excel workbook, and perform thermodynamic calculations as well as access stream and unit operation data [97] [103] [104].

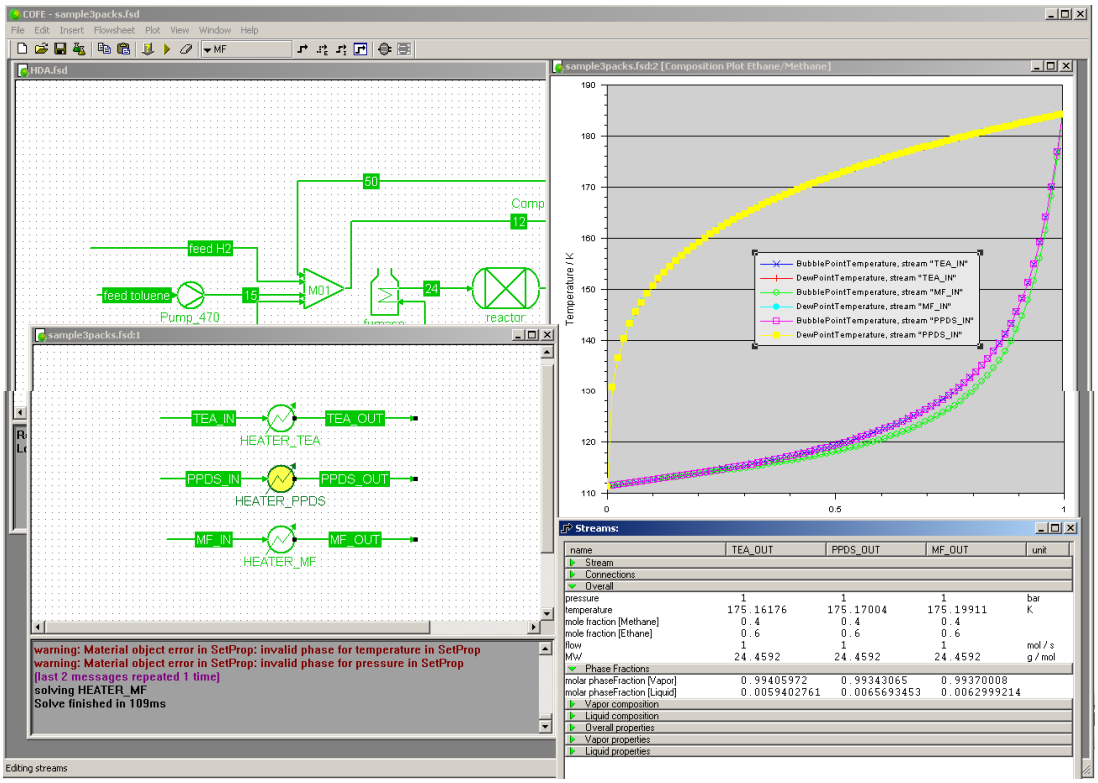


Figure 21. COFE features.

4.1.2 TEA: Thermodynamics for Engineering Applications

TEA provides an extensive pure compound data library. Additionally, over 100 methods for the estimation of more than 25 different properties are available as presented in **Figure 22** and **Figure 23**.

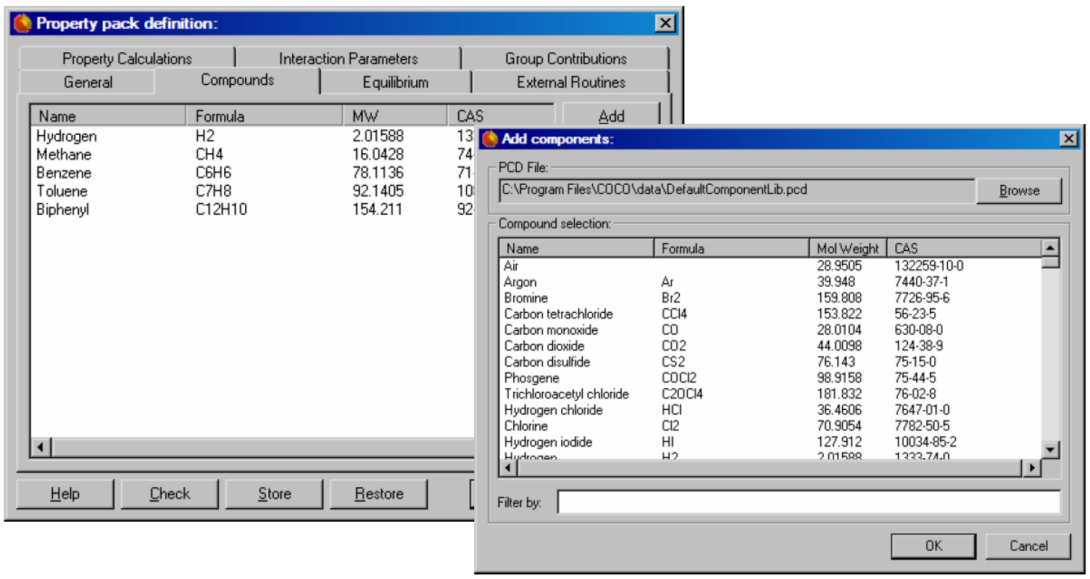


Figure 22. Data library of TEA for compounds.

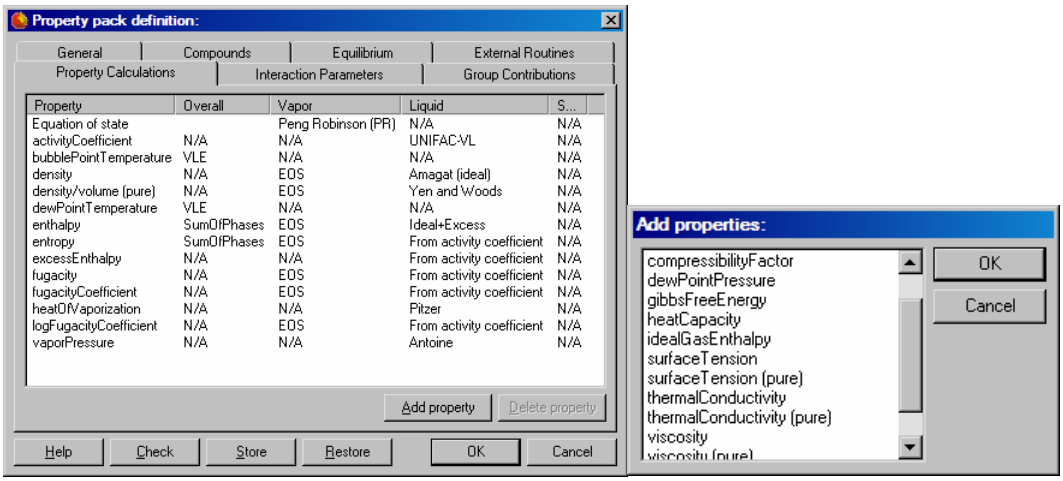


Figure 23. Data library of TEA for property calculations.

TEA is also susceptible to external property packages. The majority of the TEA's calculation methods are based on the application of ChemSep. ChemSep is a column simulator for distillation, absorption, and extraction operations which combines the equilibrium stage column model with a non-equilibrium column model in one instinctive interface. Thus, TEA offers a built-in vapor-liquid equilibrium calculator

using inside-out flash calculations, with an auxiliary Newton solution to flash calculations [97] [103] [104].

4.1.3 COUSCOUS: CAPE-OPEN Library of Unit operations

COUSCOUS provides a library of unit operations allowing engineering calculation process as **Figure 23** and **Figure 24** demonstrate. The unit operations that COUSCOUS includes are compressors, pumps, turbines, expanders, simple reactor models, flash unit operations, heaters, coolers, heat-exchangers, mixers and splitters. COUSCOUS also includes a unit operation for testing property package implementation which has the ability to calculate all derivative properties. COUSCOUS unit operations can be combined with external unit operations. Although there is a limitation regarding the number of unit operations in COUSCOUS, users has the possibility to add their own unit operation models. A distillation column is not included in COUSCOUS. However, there is a LITE version of ChemSep with a limited number of compounds and stages that can be used for this purpose [97] [103] [104].

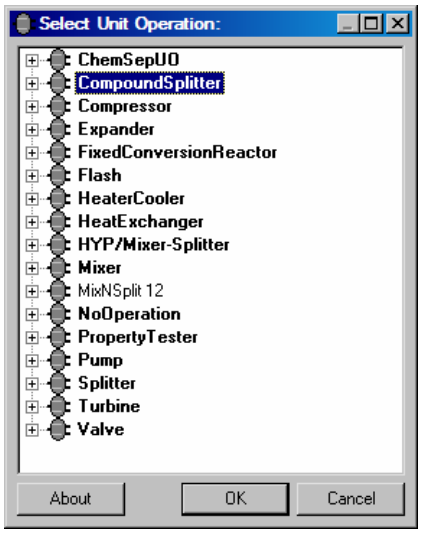


Figure 24. Unit operation library of COUSCOUS.

4.1.4 CORN: CAPE-OPEN Reaction Numeric Package

CORN features kinetic and equilibrium reactions. For kinetic reaction, pressure, temperature, concentration and mole fraction define the equilibrium constant and heats of reaction formulas [97] [103] [104].

4.1.5 CAPE-OPEN Applications

CAPE-OPEN meets international use in activities of various grave companies, such as SHELL and PDVSA INTEVEP. SHELL supports that via CAPE-OPEN, "*they are able to use in-house unit in two commercial simulation platforms without customization and so ensures consistency across the simulation platforms". Whereas,* PDVSA INTEVEP asserts that CAPE-OPEN provides them the ability "*to run the refinery reactor technology models and the in-house equilibrium calculation models in different process modeling environments"* [98] [105]. Moreover, there are numerous industrial and governmental applications of CAPE-OPEN, such as in Air Liquide that uses Simulis Thermodynamics and DIPPR database of pure substances as R&D thermodynamic standard allowing the cohabitation of four simulators, HYSYS, Belsim, Prosim, and AspenPlus. The objective of using in-house CO reactor and membrane models is to reduce development and maintenance cost. Additionally, BASF uses MultiFlash (InfoChem) as external thermodynamics server for the in-house CHEMASIM simulator, IFP and Total use an integrated approach of dynamic fluid flow modeling from the reservoir to the topside process, BP uses the ChemSep rate-based column simulator, whilst Sasol has used CO interfaces to make reactor models independent from the process simulator. Last but not least, the US Environmental Agency has integrated CAPE-OPEN's unit operations in their Pollution Prevention Toll [106] [107].

One other application of CAPE-OPEN software is in the evaluation of process sustainability. The objective is to develop a simulation process, the COWAR, resulted from the implementation of Waste Reduction (WAR) Algorithm to a CAPE-OPEN unit operation, in order to obtain environmental information and evaluate the friendliness of a chemical process. This tool has been applied to numerous processes, such as the phthalic anhydride ($C_8H_4O_3$) production, in order to estimate environmental impacts and select the best environmental process design for a chemical plant [108] [109].

Furthermore, CAPE-OPEN software has been applied in the industrial production of methanol by integrating a strict kinetic model in the simulation using the CAPE-OPEN standard. The flexibility and the accuracy of the software provide the

possibility of modeling a system by using various approaches that finally can be compared and offer the best possible solution. In case of a study of modelling a conventional methanol synthesis reactor in order to test the final composition of methanol, three different approaches were used: molar homogeneous, molar heterogeneous and mass homogeneous models, concluding similar results with previous studies [110].

The structure of the CAPE–OPEN software as well as all these applications presented above, display why to use this software in the specific occasion. First of all, it is compatible with multiple simulation environments that a company uses. It offers the ability to write code that will be adaptable to all these simulation environments, reducing the coding and software. Moreover, it enables confirmation of simulation results across simulation platforms, hence the results are not depend on the kind of software is used. Regarding the simulation environment, it provides high flexibility and consequently better bargaining position in purchasing simulation platform. Flexibility is also provided concerning the selection of simulation environment by various users. Finally, it is of free charge and easily accessible software with no significant difficulties in use [97] [103] [104].

Therefore, COCO simulation software, along with its sub-models, is going to be the main instrument of this case study in order to model a complete solid waste combustion system for energy production, which will be analyzed further in the next chapter.

5. Combined Heat and Power Generation (CHP)

Combined Heat and Power (CHP) is the simultaneous production of electricity and heat from a single fuel source and it provides distributed generation of electrical and mechanical power, waste-heat recovery for heating, cooling, or process applications and seamless system integration for a variety of technologies, thermal applications, and fuel types into existing building infrastructure. CHP is an efficient and clean technology achieving total efficiencies of 60% to 80% for electricity and thermal energy production. CHP facilities are located at or near end-user's site in order for the heat released from power production to meet the user's thermal requirements and for the power generated to meet all or a portion of the electricity needs. There are numerous benefits of combined heat and power for facility operators such as reduced energy related costs (providing direct cost savings), high reliability and low risk of power outages due to the addition of a separate power supply as well as increased economic competitiveness due to lower cost of operations. Additional benefits of CHP technology are:

- Increased energy efficiency: providing useful energy services to facilities with less primary energy input.
- Economic development value: allowing businesses to be more competitive in a global market thereby maintaining local employment and economic health.
- Reduction in emissions that contribute to global warming: high efficiency of energy use allows facilities to achieve the same levels of output or business activity with lower levels of fossil fuel combustion and reduced emissions of carbon dioxide.
- Reduced emissions of air pollutants: CHP systems can reduce air emissions of carbon monoxide (CO), nitrogen oxides (NO_x), and sulfur dioxide (SO_2) especially when state-of-the-art CHP equipment replaces outdated and inefficient boilers at the site.
- Resource adequacy: low need for regional power plant as well as transmission and distribution infrastructures.

In order to reduce the environmental impacts of energy production and use, the implementation of biomass-fueled CHP facilities has been introduced as a great and sustainable solution. The advantages of using biomass instead of fossil fuels in order to meet energy needs depend upon the intended use and the substituted fuel source. Furthermore, biomass has higher flexibility, as it can generate both power and heat, and it is more reliable, as it is an abundant resource, as an energy option than many other renewable energy resources [84].

5.1 Simulation Overview

The COCO software is going to be applied for a biomass CHP system in Thessaloniki, using as feedstock the amount of the city's MSW that are yearly disposed in a landfill. However, before applying the software, we must select the most suitable combustion technology for the available feedstock type.

There are three main incineration technologies that are widely used: (a) the fixed bed, (b) fluidized bed and (c) dust combustion as well as the feedstock characteristics, will be examined. There are differences between these incinerators concerning the operation and effectiveness in biomass combustion.

5.1.1 Fixed Bed Boiler

In fixed bed combustors through which primary air passes, the processes of drying, gasification, and charcoal combustion take place. The combustible gases produced via gasification process are burned in the combustion zone after the secondary air injection. The high endurance of this type of combustors, in moisture and ash slagging allows high temperatures between 900^{o}C and 1200^{o}C. The air supply to the system is of great importance in order to have a combustion as complete as possible. For this reason, a progressive combustion is required, which is divided in two separate phases. In the primary combustion, the primary air supply must be secured at about 25%, for low NO_x operation. However this combustion is not optimal because of the low mixing quality of air and flue gases. Thus the secondary combustion occurs in order to guarantee a better possible mixture in order to provide high efficiencies. In most cases, excess air for biomass fuels is set at 25%. Nonetheless, due to the highly volatility on a dry basis and heterogeneity in size of biomass fuels, biomass

combustion air systems are designed to provide more air. Modern designs use excess air of 40% and 60%, respectively [84] [111].

5.1.2 Fluidized Bed Boiler

The fluidized bed combustion process provides an efficient mixture of fuels and air for combustion. In this type of boilers, biomass is burned in a self-mixing process of gas and bed materials with air entering from below. The air and fuel supply into the bed is controlled in order for a continuous combustion to be realized. The typical excess air in fluidized beds is 20% or higher. Fluidized bed combustion (FBC) process is optimal for fuels with high ash sulfur, and nitrogen concentration while meeting stringent emission limitations in the same time [84] [111] [112].

Fluidized bed boilers are well known for their high flexibility concerning moisture content and their inherent biomass fuel flexibility which is incomparable to any other combustion technology. Fluidized bed combustion (FBC) can burn fuels with a wide range of calorific values, ash and moisture content. During combustion the primary air keeps fluidized the bed of sand, while secondary air is injected higher up in the furnace to achieve a staged and more complete combustion. The fluidized bed's operation temperature between 800°C and 950°C, about 100^{o}C to 200^{o}C less than in fixed bed boilers, are considerably lower than those in grate and pulverized systems. These lower temperatures prohibit the formation of nitrogen oxides (NOx) from the air combustion and allow fuels with lower ash melting temperatures to be combusted. Additionally, this process also permits the removal of sulphur dioxide (SO_2) from combustion of high-sulphur fuels simply by addition of sulphur absorbents such as limestone or dolomite in the bed. Furthermore, the fluidized bed technology reaches high capacity ranges between 20MW and 100MW, while fixed and pulverized bed combustors' capacities range from 100kW to 50MW and from 500kW to 100MW(co-firing), respectively.

Since this technology allows handling of high-ash fuels, it is therefore capable of treating a large variety of agricultural biomass residue and mixed MSW with high moisture content and extremely low heating values and can be adopted by developing countries with limited budgets and low quality waste [113] [114].

5.1.3 Pulverized Bed Boiler

The pulverized bed combustor is more suitable for wood and agricultural residues powder for large plant facilities. This type of incinerators for wood powder is available in the range of 1 MW to 30 MW. In pulverized combustors, the fuel is injected with air in the combustion chamber where combustion takes place while fuel is in suspension. Rapid and efficient combustion in pulverized bed combustors is succeeded only for small size particles (generally below 1 mm). Boilers equipped with oil burners or coal powder burners can be converted to use biomass powder fuel, or blends of biomass and fossil fuels. However, the pulverized bed combustion process is difficult to control and may suffer from too high combustion temperatures, above 1200°C which may result in high emissions of nitrogen oxides (NOx).

5.1.4 Efficiency

Boiler efficiency is defined as the percentage of the fuel energy that is converted to steam energy. Significant factors that affect the efficiency of biomass combustion are the moisture content of the fuel, the excess air injected into the boiler as well as the percentage of non-combusted or partially combusted fuels. The Council of Industrial Boiler Owners (CIBO) defines that the typical efficiency of fixed and fluidized bed combustors ranges between 65% and 85%. However, fixed bed combustors usually cannot succeed high efficiencies, with boiler efficiencies of 65%-75%. On the other hand, fluidized bed boilers as more technologically advanced can reach high efficiencies between 80% and 82% [112].

5.1.5 Operating Availability

The availability of a power generation system is the percentage of time that it is available to operate. According to the literature, a typical operating efficiency for continuous operation of both fixed and fluidized bed combustors is in around 90%. It is understandable that the feedstock availability and quality which varies seasonally also affect the plant availability. However, this is not an issue that determines the design performance of the boiler. In most cases, a well-designed biomass steam system is expected to operate with 92% to 98% availability [112].

5.2 Power Generation Technologies

CHP systems consist of specific individual components, such as prime mover (heat engine), generator, heat recovery, and electrical interconnection, configured into an integrated system. For CHP systems, prime movers usually are steam turbines, gas turbines, spark ignition engines, diesel engines, micro-turbines, and fuel cells. These prime movers can combust various types of fuels, including biomass, natural gas and coal to produce shaft power or mechanical energy. A complete CHP system consists also of additional technologies such as boilers, absorption chillers, desiccants, engine-driven chillers, and gasifiers.

Mechanical energy from the prime mover, that it is most often used to drive a generator to produce electricity, can also be used to drive rotating equipment such as compressors, pumps, and fans. Thermal energy from the system can be used in direct process applications or indirectly to produce steam, hot water, hot air for drying, or chilled water for process cooling.

Currently, the industrial sector produces both thermal energy and electricity from biomass in CHP facilities in the paper, chemical, wood products, and food processing industries. In these applications, the typical CHP system configuration consists of a biomass-fired boiler whose steam is used to generate a steam turbine in addition to the extraction of steam or heat for process use [84] [115].

5.2.1 Steam Turbine Technologies

Steam turbine is a thermodynamic device that converts the energy in high pressure and temperature steam into shaft power which can in sequence be used to turn a generator and produce electricity. In gas turbines and reciprocating engine CHP systems heat is a byproduct of power generation. On the contrary, steam turbine CHP systems generate electric power as a byproduct of steam generation. In a steam turbine CHP system, the turbine requires a separate heat source and does not directly convert fuel to electricity. The energy produced during fuel combustion is transferred from the boiler to the turbine through high pressure steam, which in turn provides movement to the turbine and generator, while steam at lower pressure is extracted from the steam turbine and used directly or is converted to thermal energy. Rankine cycle as presented in **Figure 25**, is the thermodynamic cycle usually employed. In this

cycle, water, in liquid form, is converted into high-pressure steam in the boiler and transferred to the steam turbine. The steam rotates the turbine blades, creating power that is turned into electricity through a generator. Afterwards, a condenser and pump collect the steam exiting the turbine, and feed it into the boiler completing the cycle.

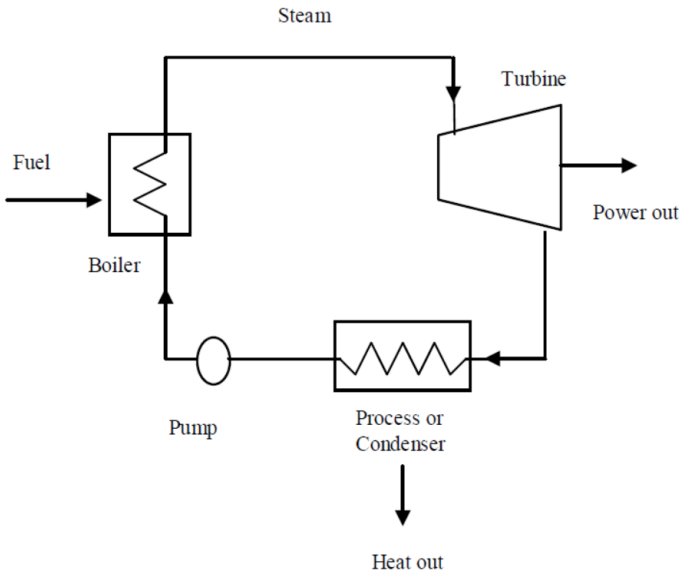


Figure 25. Boiler/Turbine System (Simple Steam Turbine Power Cycle).

There are several types of steam turbines, each one for a different purpose:

(a) Condensing steam turbines, such as those in **Figure 25** and **Figure 26**, are only used for power applications and expand the pressurized steam to a low pressure point where a steam and liquid water mixture is exhausted to a condenser at vacuum conditions.

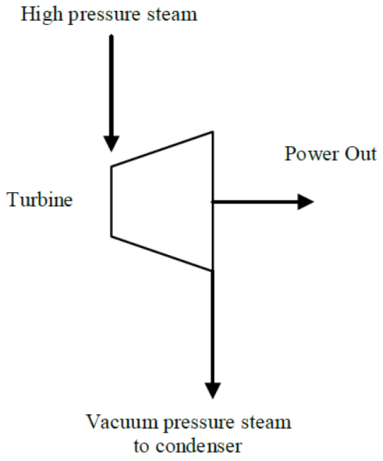


Figure 26.Condensing Steam Turbine.

(b) Back-pressure turbines, as shown in **Figure 27** exhaust the entire flow of steam to the process or facility at the required pressure.

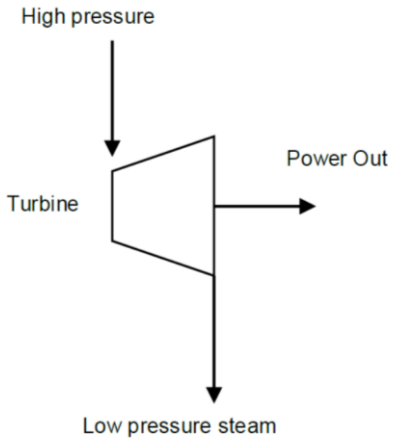


Figure 27. Back-pressure (non-condensing) Steam Turbine.

(c) Extraction turbines, as shown in **Figure 28**, have openings in their casings for extraction of a portion of the steam at some intermediate pressure for use in other processes or space heating.

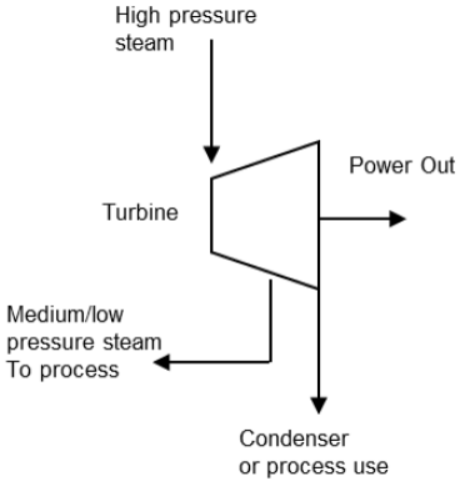


Figure 28. Extraction Steam Turbine.

Steam turbine power generation has been in use for about 100 years, when they replaced reciprocating steam engines due to their higher efficiencies and lower costs and they are widely used in CHP facilities. The capacity of steam turbines can range from 50 kW to several hundred MW for large utility power plants [84] [115].

6. Case Study

6.1 The situation in Greece

Land disposal of MSW still remains a crucial issue in Greece. Although 18% of MSW is recycled at source, the remaining 82% is disposed without any prior treatment, from which the 52% ends up in landfills, whilst the 40% is disposed illegally in non-approved sites. Currently, Greece produces approximately 5.58 million tons of MSW annually in which the contribution of the greater area of Athens is 39%, while this of the city of Thessaloniki reaches 9% of the total production [46] [116] [117]. According to **Table 8** and **Table 9,** which illustrate the chemical composition as well as the heating values in a dry basis of MSW generated in Greece, the total High (HHV) and the Low Heating (LHV) values, recorded in 2010, are 11.69 and 9.75 respectively [118].

Table 8. Chemical Waste Composition, HHV and LHV Values in a dry basis, in Greece.

Waste Fraction	Moisture (%)	C (%)	H (%)	O (%)	N (%)	S (%)	Ash (%)	HHV (MJ/kg)	LHV (MJ/kg)
Paper/cardboard	70	48	6.4	37.6	2.6	0.4	5	7.08	3.96
Food waste	6	43.5	6	44	0.3	0.2	6	14.49	13.03
Plastic	2	60	7.2	22.8	0	0	10	26.11	24.48
Textile	10	55	6.6	31.2	4.6	0.2	2.5	20.17	18.47
Metals	3	4.5	0.6	4.3	<0.1	0	90.5	1.55	1.35
Glass	2	0.5	0.1	0.4	<0.1	0	98.9	0.23	0.16
Wood waste	20	49.5	6	31.2	4.6	0.2	2.5	15.96	14.16
Yard waste	60	47.8	6	38	3.4	0.3	4.5	7.94	5.16
Others	20.5	20.91	2.39	12.78	0.4	0.1	42.93	6.27	5.69
Total calorific values								11.69	9.75

Table 9. Waste Heating Value and Physical Waste Composition, in Greece.

Waste Fraction	**Composition (%)**
Organics	40
Paper/cardboard	30
Plastic	14
Metals	3
Glass	3
Leather-Wood-Textile	2
Inert	3
Other	6

6.2 The case of Thessaloniki

Thessaloniki is the second largest city of Greece located in the northern part of the country in the region of Central Macedonia. It occupies an area of 18,811 km^2 with 1,881,869 inhabitants. The Greater Metropolitan area of Thessaloniki consists of 14 Municipalities, most of which have high population density, with the amount of inhabitants in the greater area reaching 1,110,312 people, whilst approximately 352,000 people live in Municipality of Thessaloniki [116] [119].

For the last 30 years, the whole area of Thessaloniki, regarding MSW management, is served by only one sanitary landfill located 35 km southeast of the city with a total area of 100 ha, the greater part of which has already been covered.

Table 10 demonstrates the annual generation of MSW in the greater area of Thessaloniki, in conjunction with the rise of its population through the years. From this table, there is a noticeable decrease of the rate of waste production from 2006 to 2012 which results in a decrease of the total amount of solid wastes in 2012 regardless of the population increase [116].

Table 10. Generation of MSW in the Greater Area of Thessaloniki.

Year	1987	1998	2006	2012
Population	750,000	1,000,000	1,100,000	1,110,000
MSW production (kg/person/year)	280	460	560	402
Total MSW production (kg/year)	210,000,000	460,000,000	616,000,000	447,000,000

More analytically **Figure 29** displays the variation of solid waste collection in the Municipality of Thessaloniki for the 2001-2014 time period. Despite the fact that there were no data for the year 2007, in general, there is a prominent increase of the waste amount from 2005 to 2009 with a pick of 195,282 tons of solid waste collected in 2009. Nevertheless, a significant decrease of this amount occurs after 2010 to be almost stabilized in the last two years (2013-2014) between 112,000 and 113,000 tons [119].

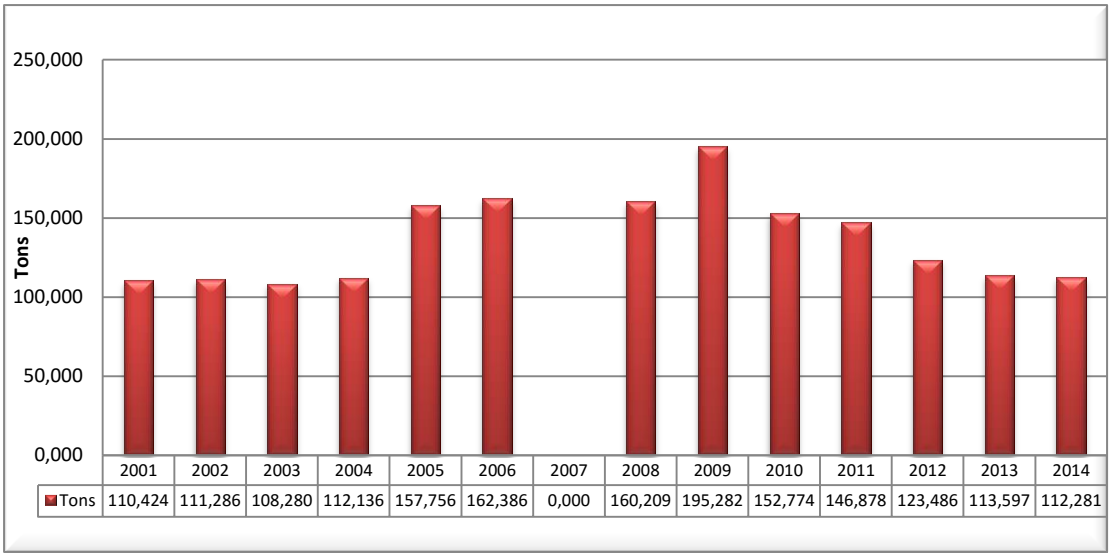


Figure 29. Thessaloniki's Variation of Solid Waste Collection Data 2001-2014.

Figure 30 illustrates the monthly variation of solid waste production from the city, that was finally disposed to the landfilled facility during the 2012-2013 period [119] [120]. The maximum waste disposal was recorded in September, whilst there are no substantial differences between the monthly landfilled waste amounts, as Thessaloniki is a high residential city either of constant habitants or tourists, during the whole year. Additionally, while the total amount of solid waste for the region of Thessaloniki, consisting of 14 Municipalities, was almost 407,000 tons in 2012, the disposed solid waste only from the city itself was approximately 123,000 tons. However, in 2014 the total amount of MSW of the city was diminished at about 112,000 tons.

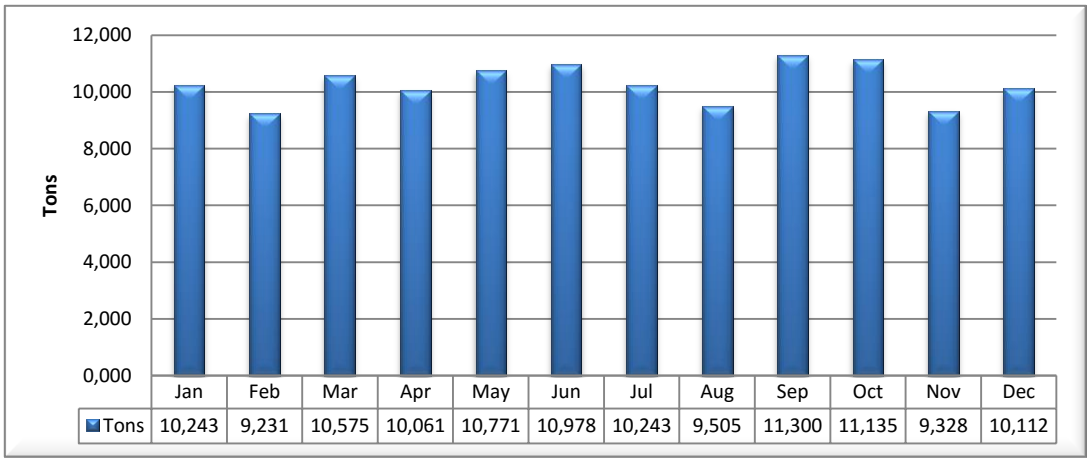


Figure 30. Solid Wastes to Landfilled Facility per month in 2012 for the City of Thessaloniki.

6.2.1 Physical and Chemical Characteristics of MSW in Thessaloniki

Regarding the composition of Thessaloniki's MSW, according to a specific study, the results of which are presented in **Table 11**, there are significant fluctuations and differences in the waste composition from 1987 to 2012. Between these years an increase in the organics fraction and a decrease in paper and plastic were observed, as a result of recycling and population increase [119] [120].

Table 11. Composition of Thessaloniki's MSW from 1987 to 2012.

Waste Fraction	1987	1998	1999	2004	2006	2012
Organics (%)	61.1	35.75	47	38.34	36.13	47.6
Paper (%)	17.7	29.21	23	26.66	25.86	21.9
Plastic (%)	7.2	17.9	13	17.9	19.71	12.1
Glass (%)	4.1	4.61	3	3.61	3.66	3.5
Metals (%)	5.9	3.4	4	4.03	3.39	3.9
Other (%)	4	9.13	10	9.46	11.25	11

Furthermore, the average composition of Thessaloniki's MSW, which is presented in **Figure 31**, appears to be similar to that of other European cities with a similar population [119] [120].

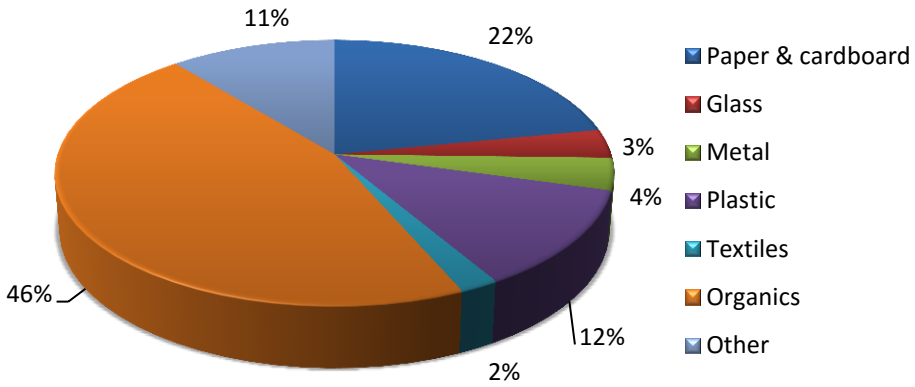


Figure 31. Composition (% by weight) of Thessaloniki's MSW in 2012.

In general, MSW are divided in two categories according to their combustion ability: the combustible wastes such as fermentable materials, plastic, paper, wood, rubber, leather, fabrics, etc. and the incombustible wastes like glass, metals, aggregates etc. The moisture and ash content of MSW as well as the combustible material content depend on their composition. Combustion and more specifically energy recovery of waste is coupled with the amount of heat that can be released during combustion. The amount of heat emitted during combustion of unit mass of a material is expressed as calorific value of this material. Depending on the physical state of water vapor produced during combustion, the calorific value is referred to as higher (water vapor condense into liquid) and lower (the steam remains in vapor phase). The calorific value of a material depends on the content of the basic fuel elements, which are carbon and hydrogen and to a lesser extent sulfur. Important parameters for the combustion of a material constitute the moisture and ash content. Moisture contained in the waste is an obstacle for an efficient combustion as it requires a significant amount of energy to be removed in order to enable the waste to be burned and to perform the containing thermal load. On the other hand, the ash consists of minerals contained in waste (metal, glass, and other aggregates such as soil) which cannot be burned and must be removed from the site of waste combustion [121]. Wastes are burned when the moisture content does not exceed 50%, ash content 60% and the fuel must be at least 25%, more specifically, when the lower calorific value is 3,350kJ/kg.

6.2.2 MSW Combustion

Waste Combustion is the process of oxidation of waste at high temperature in the presence of oxygen. During this process the waste decomposes thermally in the presence of excess air. The heat treatment process of waste is affected by the following parameters:

- Homogeneity,
- The size of the particles,
- Thermal conductivity,
- The ignition temperature,
- Specific weight,
- Calorific value of fuel,
- The quantitative composition of flammable material, ash and water,

- The volatile content,
- Hazardous substances content and
- The melting point of ash,

The specific surface and conduction affect the speed of the thermal process. The effect of these parameters is difficult to determine, due to the heterogeneity of the materials. The ignition temperature is calculated at 400°C. The density of the waste depends on the containing humidity and varies between 150-350kg/m^3. The ash content of MSW ranges from 26% to 33%wt. Moisture is 25-50%wt. [121].

According to previous studies the chemical characteristics of MSW for Thessaloniki is presented in **Table 12**, moisture content is 27.7%, the ash content 29% while the HHV is 21.58MJ/kg and the LHV is 8.42MJ/kg. The physical and chemical characteristics of Thessaloniki's MSW indicate that the MSW is suitable for energy recovery. The high concentration of paper, plastic and other combustible materials indicate incineration as a feasible treatment solution [115] [116] [120]**.**

Table 12. Chemical Composition of MSW in Thessaloniki.

Parameter	**Average mean values (wet weight)**
Moisture (%)	27.7 %
Ash (%)	29 %
C (%)	43.6 %
O (%)	19.7 %
H (%)	5.9 %
N (%)	1.8 %
C/N	27
Higher Heating Value (H_o) (kJ/kg)	21,580 kJ/kg
Lower Heating Value (H_u) (kJ/kg)	8,420 kJ/kg

Considering that the total feedstock of the city in 2014 was around 112,000 tons and according to the MSW composition, the total solid biodegradable fraction of Thessaloniki's MSW for the specific year period was 104,000 tons. Thus, regarding the composition in 100 kg of dry and ash free biomass, in 104,000 tons of input biomass the quantity of C, H and O will be 45,300 tons, 6,100 tons and 20,500 tons, respectively, as **Table 13** demonstrates.

Table 13. Chemical Combustion Processes.

Dry-ash free biodegradable biomass	Input			Output	
	C	H	O	CO_2	H_2O
100 kg	43.6 %	5.9 %	19.7 %		
104,000 tons	45,300 tons	6,100 tons	20,500 tons	166,100 tons	55,000 tons

Through the stoichiometry of combustion process (1) and (2), 166,100 tons 55,000 tons of CO_2 and H_2O are produced, respectively, while the total quantity of O_2 required for this process is 160,000 tons as it is presented in **Table 14Table 14**.

$$(1)\ C + O_2 \rightarrow CO_2 \qquad (2)\ 2H + {}^{1}/_{2}\, O_2 \rightarrow H_2O$$

$$1\ mol + 1\ mol \rightarrow 1\ mol \qquad 2\ mol + 1/2\ mol \rightarrow 1\ mol$$

Table 14. Total Oxygen Requirement for Combustion.

(1)	O_2	120,800 tons
(2)	O_2	48,800 tons
O_2 existed		20,500/2= 10,250 tons
Total O_2 needed for combustion		160,000 tons

6.3 Fluidized Bed Boiler CHP in Thessaloniki

According to similar biomass CHP facilities, the specific project presents the simulation of a Fluidized Bed Boiler CHP facility in Thessaloniki, through the COCO simulator software. Apart from the fluidized bed combustor, the facility consists of a steam back-pressure steam turbine, a low-pressure steam turbine, a condenser and a low-pressure pump. The annual feedstock of the city that is available for processing is 104,000 tons/year. Thus, considering a typical utilization of the plant at 90% annually, as referred in Chapter 5, the biomass fuel feed is about 316 tons/day. Biomass fuel characteristics are presented in **Table 15** [84] [115].

Table 15. Biomass Fuel Characteristics.

Biomass Fuel Characteristics	
Biomass Fuel Feed	316 tons/day
Moisture content	27.7 %
Energy content (LHV as received)	8.42 MJ/kg

6.3.1 Fluidized Bed Boiler

The fluidized bed combustion process has been in use for more than 25 years and it is considered to be now an efficient and environmentally friendly technique. The advantages of this combustion process outweigh the other combustion technologies, regarding efficiency, energy production, capacity ranges and environmental sustainability [113] [114].

Fluidized Bed Combustion technology is the dominant combustion process for MSW treatment with the lowest emissions, worldwide. Great Waste-to-Energy facilities in the world are based in this type of technology. Among these plants are: the Robbins Resource Recovery Facility (Robbins, IL), the Toshima Incineration Plant (Tokyo, Japan), the TIR Madrid Plant (Madrid, Spain), the Valene Plant (Mantes la Jolie, France), the DERL Energy-from-Waste Facility (Dundee, Scotland), and the Lidköping Waste-to-Energy Plant (Lidköping, Sweden) [122].

Thus, the low temperatures of the fluidized bed combustor, the high capacity ranges, the flexibility concerning the moisture and fuel type, the ability to burn biomass with a low ash melting temperature which normally makes the combustion chamber, the

boiler heating surface and the lining sticky, the efficient mixing action of the bed as well as the low excess air result in a suitable and efficient method for Energy Recovery from Thermal Conversion of Municipal Solid Waste (MSW) and Refuse Derived Fuel (RDF) [41] [122] [123].

For the specific input rate of biomass the energy requirement of the incinerator for an efficient combustion is 30 MW, based on the LHV of biomass feedstock.

For the CHP simulation in COCO simulator we choose to compare three different pressure types of fluidized steam generators. More specifically subcritical boilers of 2MPa, 5MPa and 10 MPa are going to be examined. Moreover, a relatively new technology of supercritical steam generators exists and it is used for the production of electricity at supercritical pressures. In contrast to subcritical boilers, supercritical boilers operate at high pressures, over 22 MPa, where the physical turbulence of boiling does not occur and the fluid is neither liquid nor gas but a super-critical fluid. On the other hand, typical subcritical fluidized boilers operate between 1 MPa and 10 MPa. Although supercritical boilers are more expensive than similar sized subcritical boilers, the higher initial capital investment can be offset by the lifecycle savings yielded by the technology's improved efficiency, reduced emissions, and lower operating costs, as a result of the higher steam temperature and pressure parameters [122]. However, existing supercritical steam generator technologies are used only for pulverized-coal-fired power plants and not for biomass yet. Hence, in this project we are going to examine the application of these different pressure boilers in a CHP plant.

Taking into account other similar projects of Fluidized Bed CHP plants, the characteristics of three boilers selected for the specific project are presented in **Table 16.**

6.3.2 Steam Turbines

Regarding the steam turbines for the specific simulation, taking into account the relative bibliography, it was decided to use two sequential steam turbines. The first one is a High Pressure (HP) and back-pressure steam turbine which receives the high pressure steam produced from the boiler, while the second one is a Low Pressure (LP) condensing turbine which exhausts the low pressure mixture of saturated vapor and

liquid water directly to the condenser [41] [122] [123]. The characteristics of these turbines are presented in **Table 16**.

Table 16. Characteristics of FBB CHP in Thessaloniki.

Fluidized Bed Boiler CHP in Thessaloniki			
Biomass Fuel Characteristics			
Biomass Fuel Feed (tons/day)	316		
Moisture content (%)	27.7		
Energy content (LHV as received) (MJ/kg)	8.42		
Biomass Conversion			
Boiler efficiency (zero moisture) (%)	84-95		
Boiler efficiency (moisture adjusted) (%)	80		
Heat input to boiler (MW)	30		
Plant availability factor	0.9		
Boiler Steam Conditions	**2MPa Boiler**	**5MPa Boiler**	**10MPa Boiler**
Boiler output pressure (MPa)	2	5	10
Boiler output temperature (°C)	540	540	540
Nominal steam flow (tons/hr)	31.4	31.7	32.2
CHP Back-Pressure High Pressure Turbine			
Process steam conditions (MPa [saturated])	1	1	1
Process steam flow (tons/hr)	31.4	31.7	32.2
HP-Turbine Efficiency (%)	90	90	90
CHP Low Pressure Turbine			
Process steam conditions (MPa [saturated])	0.1	0.1	0.1
Process steam flow (tons/hr)	31.4	31.7	32.2
LP-Turbine Efficiency (%)	90	90	90
Condenser-Heat Exchanger			
Liquid Water output Temperature (°C)	48		
Feed Pump			
Liquid Water output Pressure (MPa)	2	5	10
Feed Pump Efficiency (%)	80	80	80

6.3.3 Condenser

After the condensing turbine the mixture of saturated vapor and liquid water passes through an array of tubes, cooled by water from a river, lake or cooling tower, and it is condensed into liquid water. The vacuum conditions in the condenser are caused by the near ambient cooling water causing condensation of the steam turbine exhaust steam in the condenser. For this case it is elected a typical temperature for condenser at 48^{o}C at constant pressure because of the Rankine cycle in **Figure 32** [41] [122] [123].

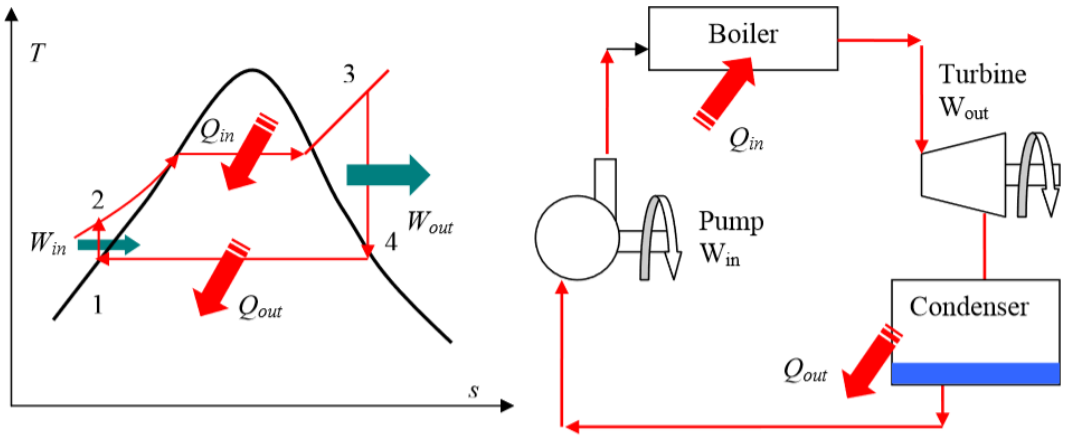


Figure 32. Rankine Cycle of a CHP unit.

The temperature-entropy (T-s) diagram, given in **Figure 32**, operates in the following steps:

1-2 Isentropic Compression in the Pump. The feed pump raises the pressure of the condensate. Due to the low specific volume of liquids, the pump input work is relatively small.

2-3 Isobaric Heat Addition in the Boiler. In this stage the high pressure liquid enters into the boiler from the feed pump, it is heated and converted into saturated vapor.

3-4 Isentropic Expansion in the Turbine. The vapor expansion produces work which can be converted to electricity.

4-1 Isobaric Heat Rejection. The saturated mixture of vapor and liquid leaves the turbine and it is condensed at low pressure in the condenser. The vapor's pressure remains below atmospheric pressure and it approaches the saturation pressure of the operating fluid at the cooling water temperature [41].

6.4 Fluidized Bed Boiler CHP in Thessaloniki-COCO Simulation

As it has already been referred the three different pressure types of fluidized bed boiler will be examined in COCO. The characteristics of thee three fluidized bed boiler CHP are introduced as data in COCO simulator that provides a graphical simulation of the biomass CHP plants as well as the amount of energy production of

each facility. At this point a step-by-step presentation of the COCO process simulation is going to be illustrated.

The first step, after opening COFE flowsheet programme, as presented in **Figure 33.,** is to define the components for the simulation. In the specific occasion, water is the only component of the cycle. Thus, clicking the "Settings" button on the left side of the COFE window, in **Figure 34**, the "Flowsheet Configuration" window will open. With the tab "Water" selected, in **Figure 35**, click the Add button.

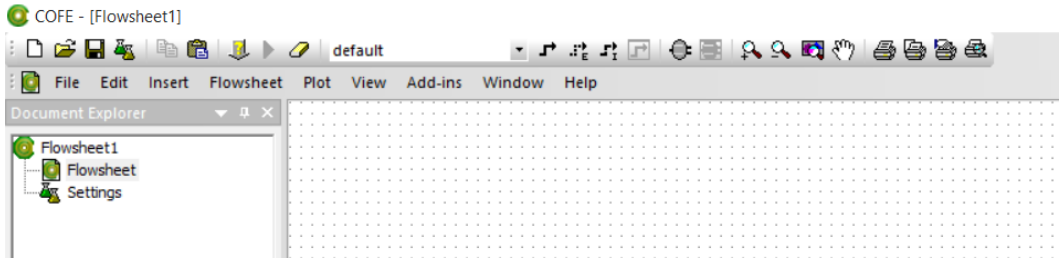


Figure 33. COFE Flowsheet

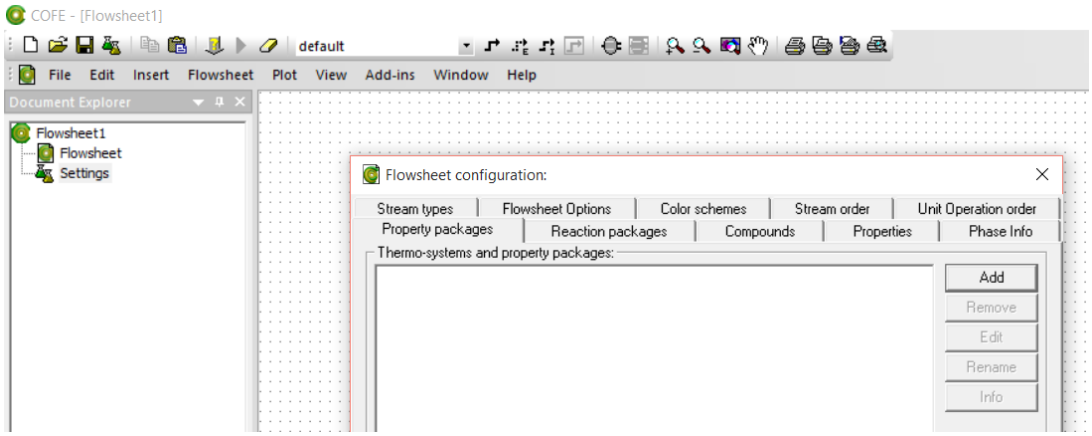


Figure 34. Flowsheet Configuration.

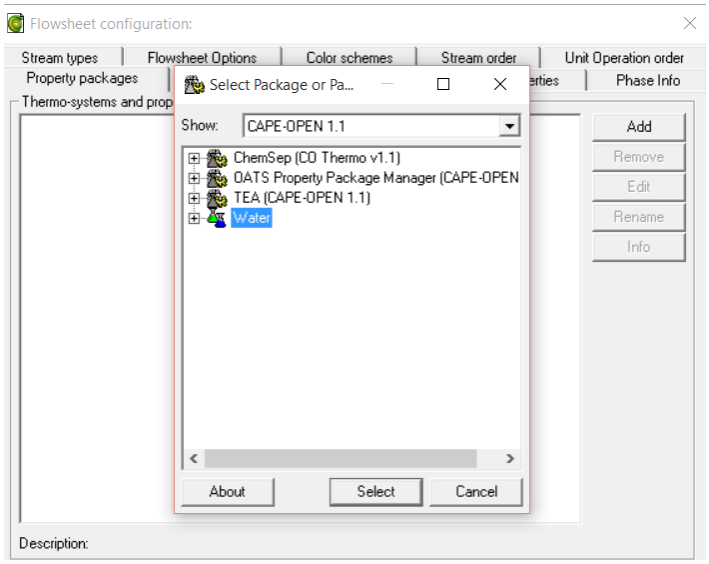


Figure 35. Selection of Package or Package Manager.

Now we have our new property pack "Water" configured for use, as presented in **Figure 36** and the simulation is about to begin.

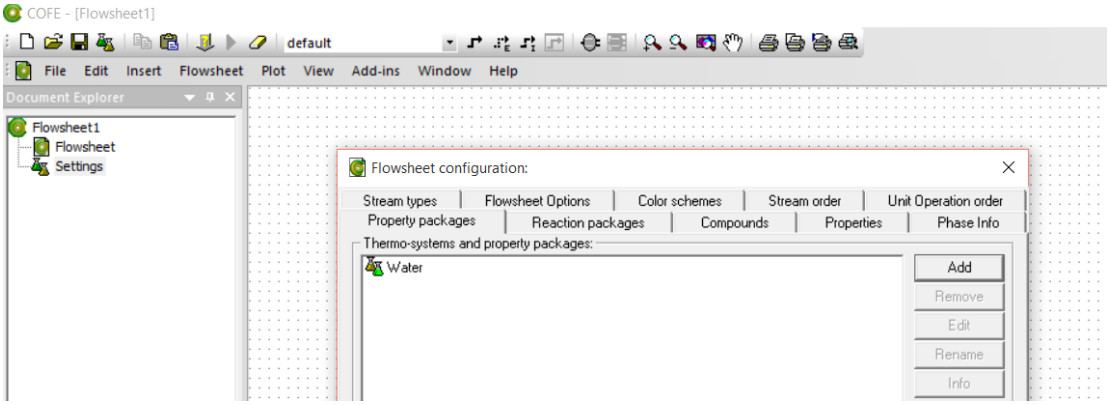


Figure 36. Property Configuration.

Now we will add the units of the CHP installation to the flowsheet. Under the “Insert” menu, in **Figure 37** and selecting “Unit Operation” we have the ability to insert any unit for the process. The first unit must be added is the boiler as it is obvious in **Figure 38**.

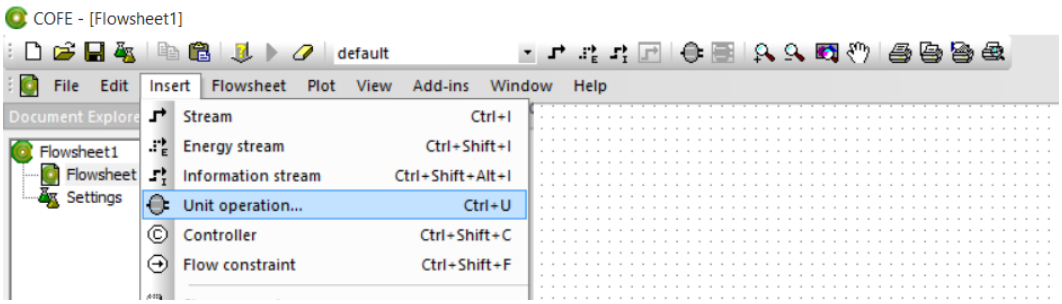


Figure 37. Insert Unit Operation.

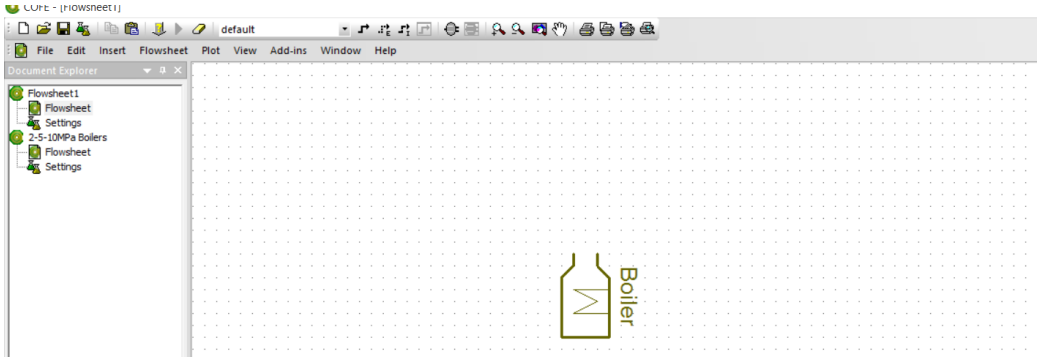


Figure 38. Insert of Boiler.

Then clicking again the “Insert” menu and selecting “Stream” we can insert a material stream and then clicking on the left side of the boiler, we connect a feed stream to the boiler unit. Repeating the same process and then clicking on the right side of the boiler, we can insert the terminate stream, as **Figure 39**, shows.

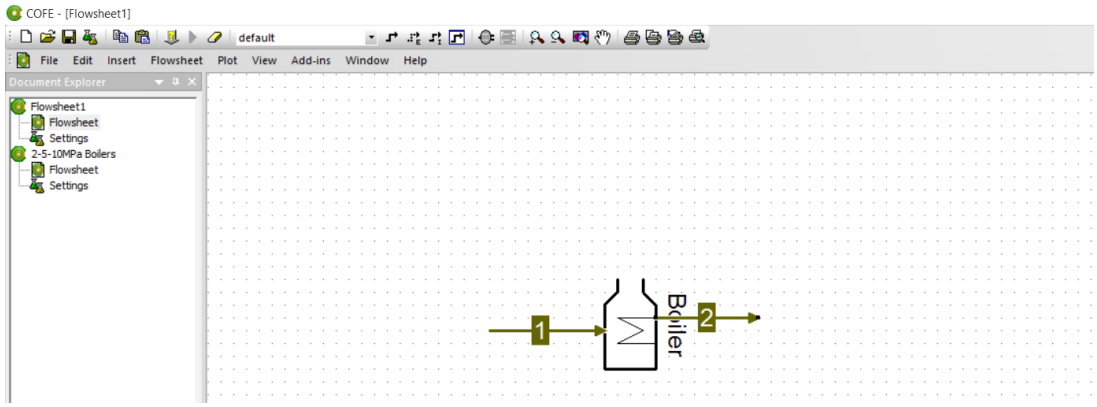


Figure 39. Insert of Streams.

Now we need to define conditions in the feed stream. Double-click or right-click on stream 1 and select Edit/view streams. A window, like this in **Figure 40**, opens that allows us to specify stream 1. Here we define the pressure, temperature and flow units in MPa, ^{o}C and tons/hr respectively, as **Figure 41** shows. For the specific example we use the 10MPa fluidized boiler, thus, the flow rate of water, in 25 ^{o}C, that corresponds to 30MW of boiler capacity is 32.2 tons/hr.

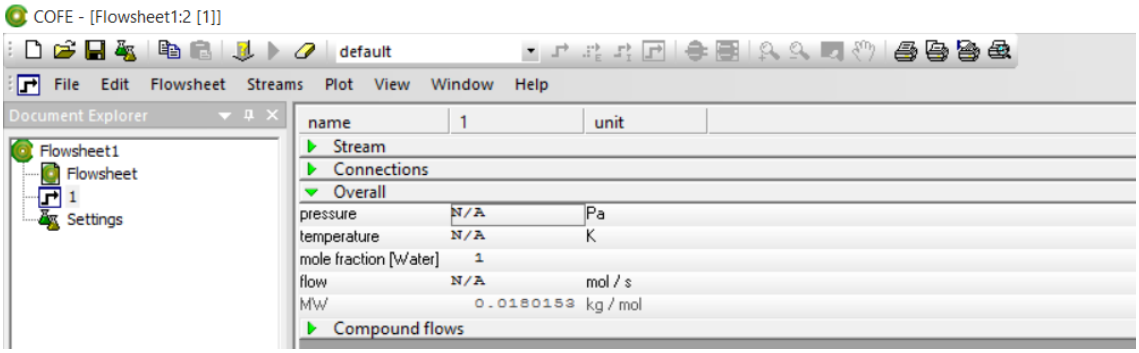


Figure 40. Stream Specification.

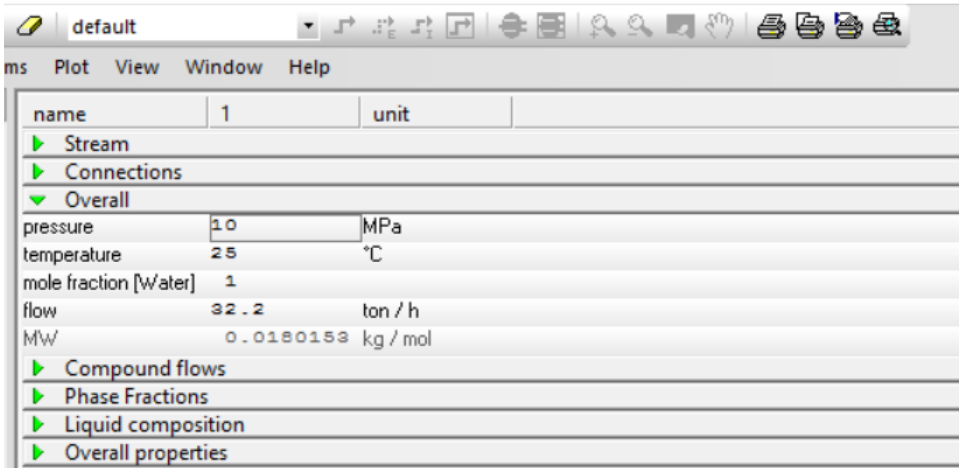


Figure 41. Stream Specification.

Next step is to specify conditions for the boiler, as presented in **Figure 42**. Double-click or right-click on boiler and select Edit unit operation in order to enter conditions for the unit: Pressure drop of 0 MPa, Temperature of 540 °C and Heat duty of 30MW. Note that with the "Show GUI" (graphical user interface) button at the bottom of the Unit operation window, we could interface to specify the unit.

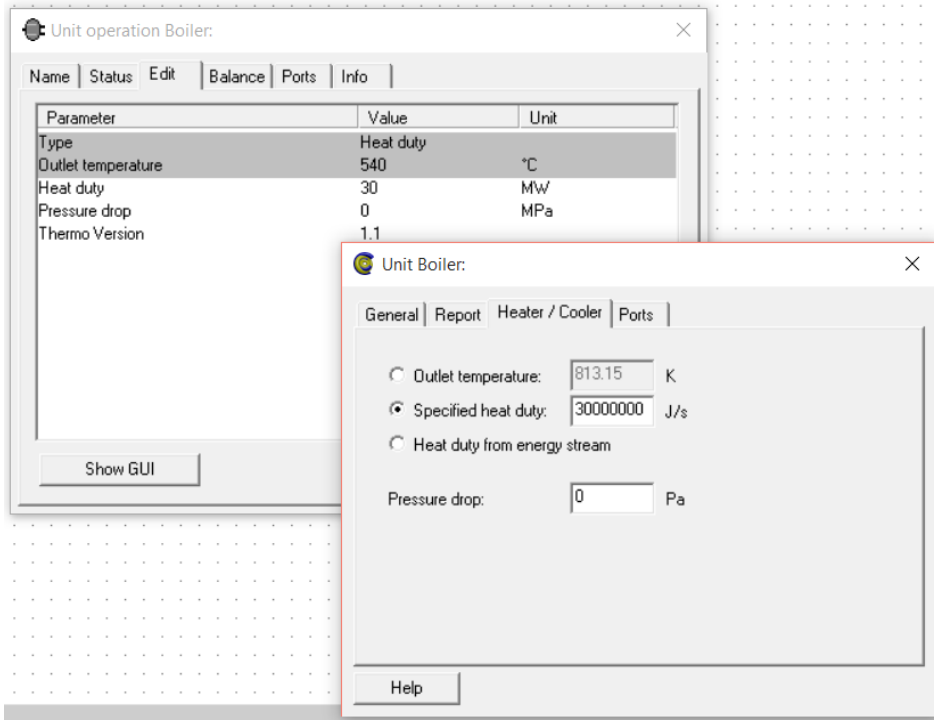


Figure 42. Unit Operation Boiler Specification.

We must be sure that we have specified enough conditions so that the stream 1 and boiler unit are turn into black as in **Figure 43**. Then, under the "Flowsheet" menu, we select the "Solve" button. When the system is turn into green then it is solved and we can observe the situation of the outflow stream in **Figure 44**.

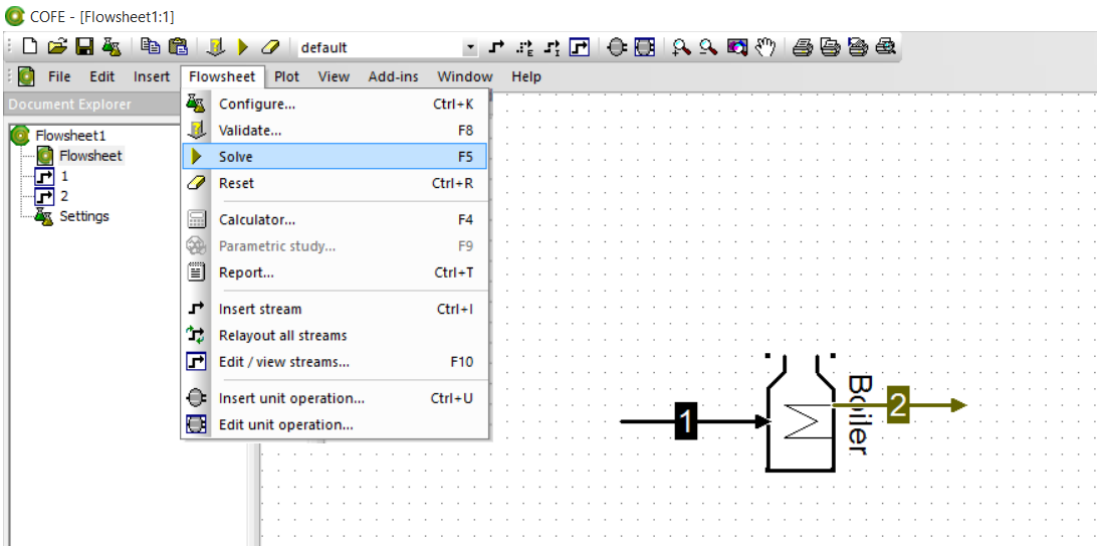


Figure 43. Solution of the specified system.

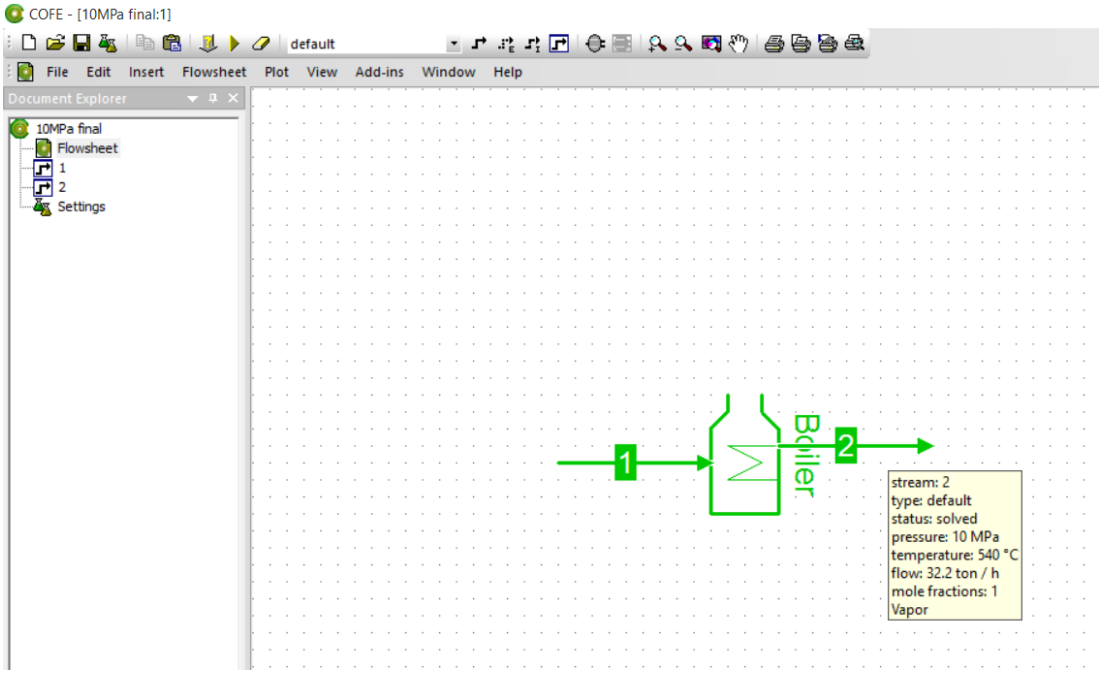


Figure 44. Solution of the system.

Afterwards, we have to insert the HP and LP turbines. As previously, under the "Insert" menu, and selecting "Unit Operation" we add an expander unit as **Figure 45** and **Figure 46** show.

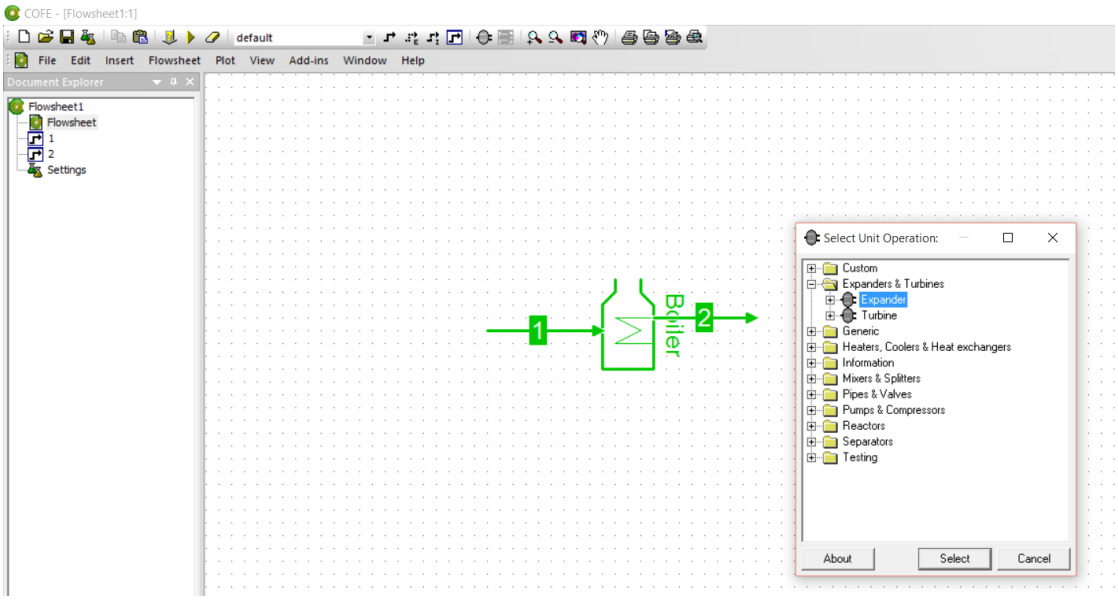


Figure 45. Insert Unit Operation Expander.

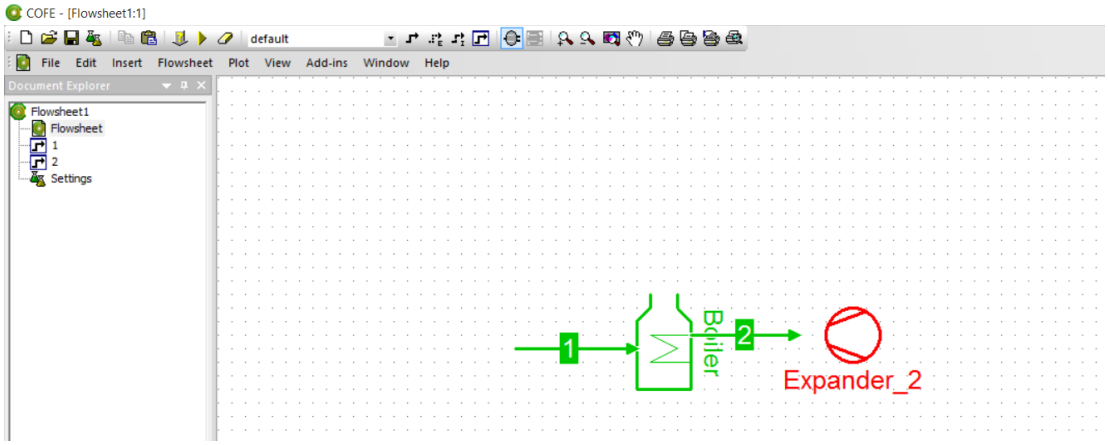


Figure 46. Insert Expander.

We rename the Expander to HP-Turbine and we define its conditions as we did previously, in case of the boiler. We specify conditions for the HP-Turbine, as presented in **Figure 47**. Double-click or right-click on boiler and select Edit unit operation in order to enter conditions for the unit: Pressure drop of 9MPa, Pressure of 1Mpa and Efficiency of 0.9. After we add the stream 3 and when the unit turns to black, as in **Figure 48**, we can solve the system.

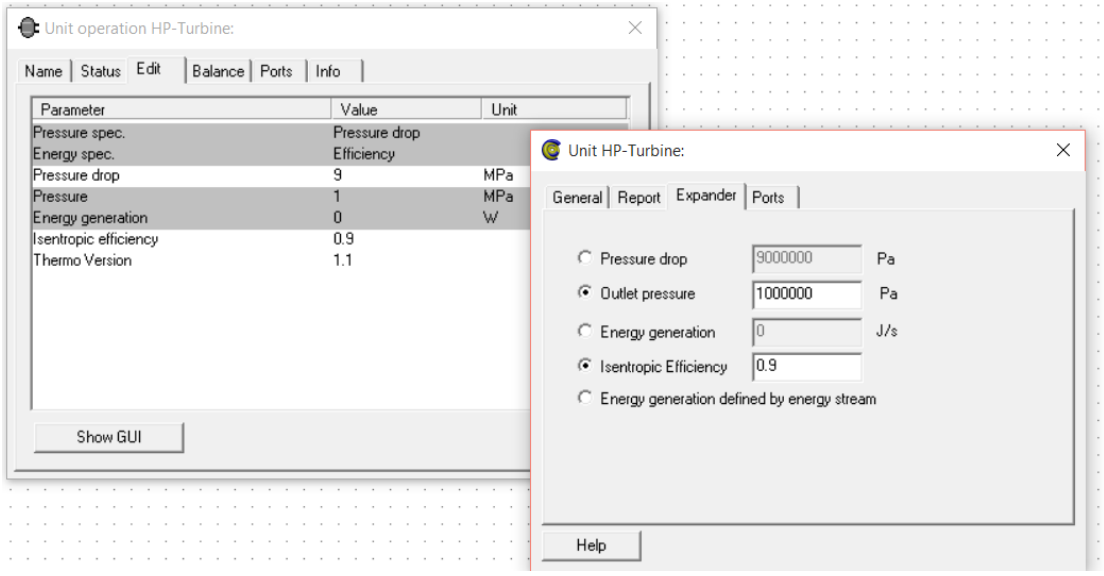


Figure 47. Unit Operation Expander Specification.

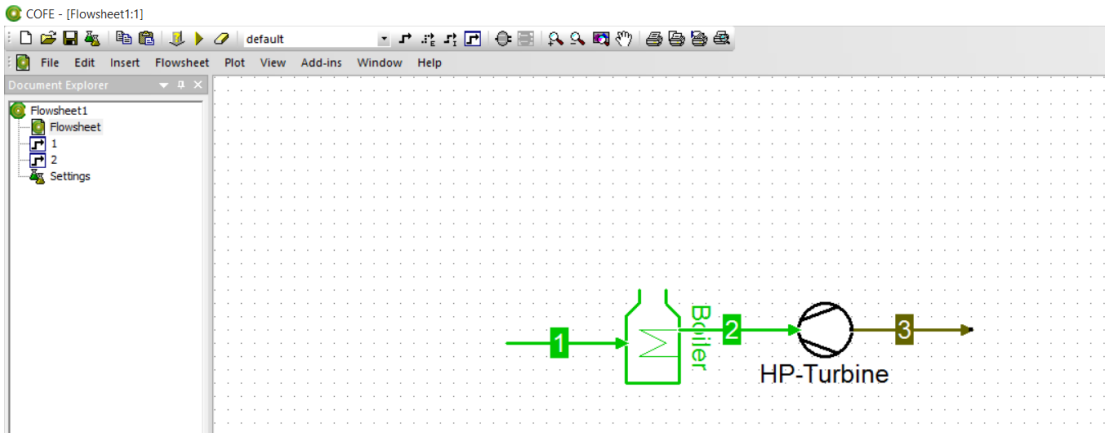


Figure 48. Specified HP-Turbine.

When the system is turn into green then it is solved and we can observe the situation of the outflow stream in **Figure 49**. In this stage, saturated vapor exits from the turbine at 233.756^{o}C, 1MPa, with a constant flow rate.

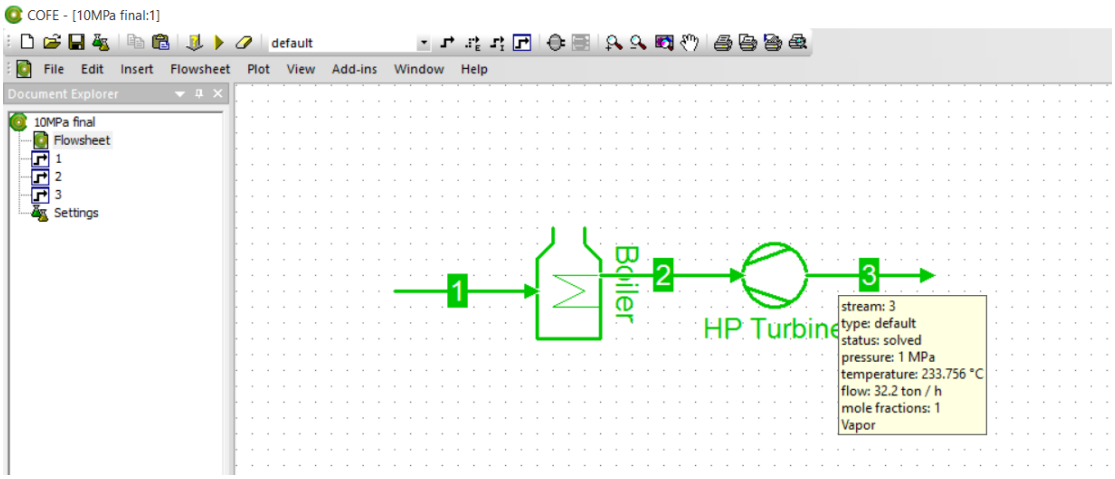


Figure 49. Solution of the system.

Repeating the same process, we add the LP-Turbine, as shown in **Figure 50**, whose conditions are: Pressure drop of 0.9MPa, Pressure of 0.1MPa and Efficiency of 0.9. **Figure 51** illustrates the solution of the new system, where some condensation occurs resulting a saturated mixture of vapor and liquid water at 0.1MPa and 99.60^{o}C.

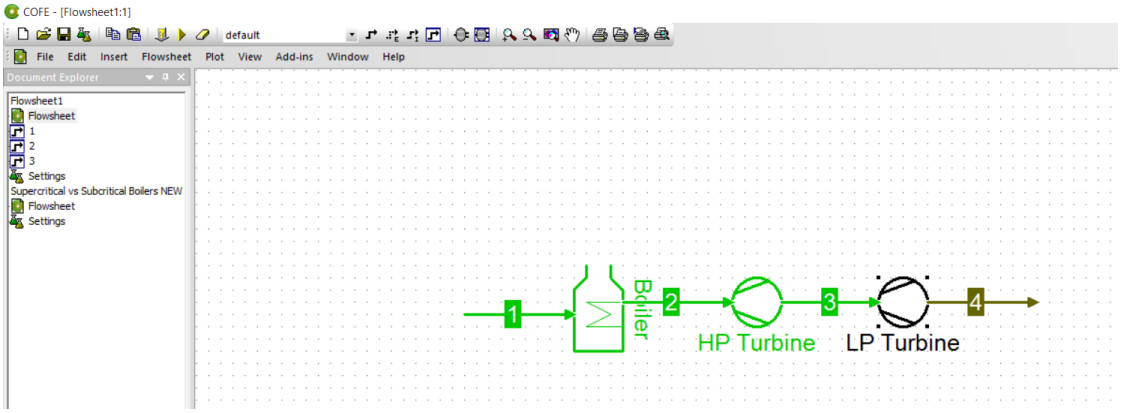


Figure 50. Insert LP-Turbine.

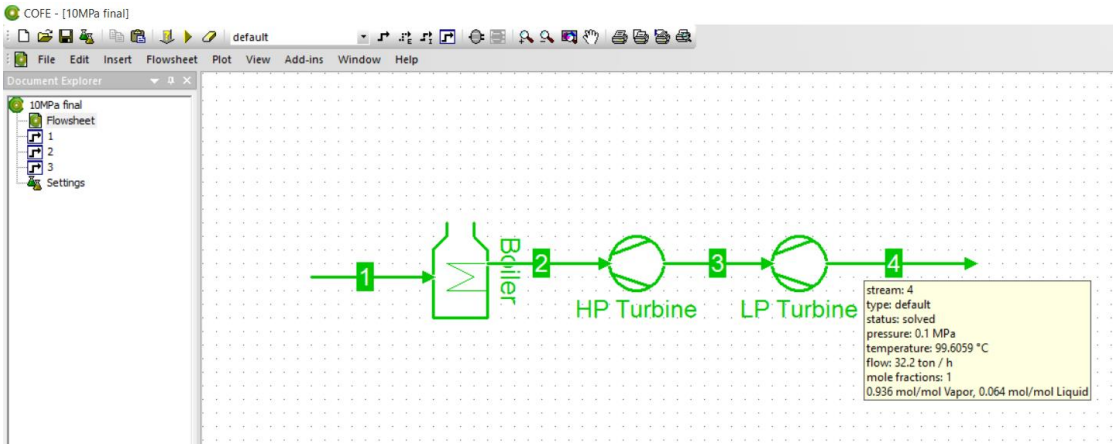


Figure 51. Solution of the system.

Figure 52 and **Figure 53** show that the same process is followed for the condenser unit as well. Here, the outlet temperature is defined, according to similar facilities, at 48^{o}C, while heat is rejected at constant pressure. The wet vapor exiting from the LP-Turbine enters to the condenser to become a saturated liquid.

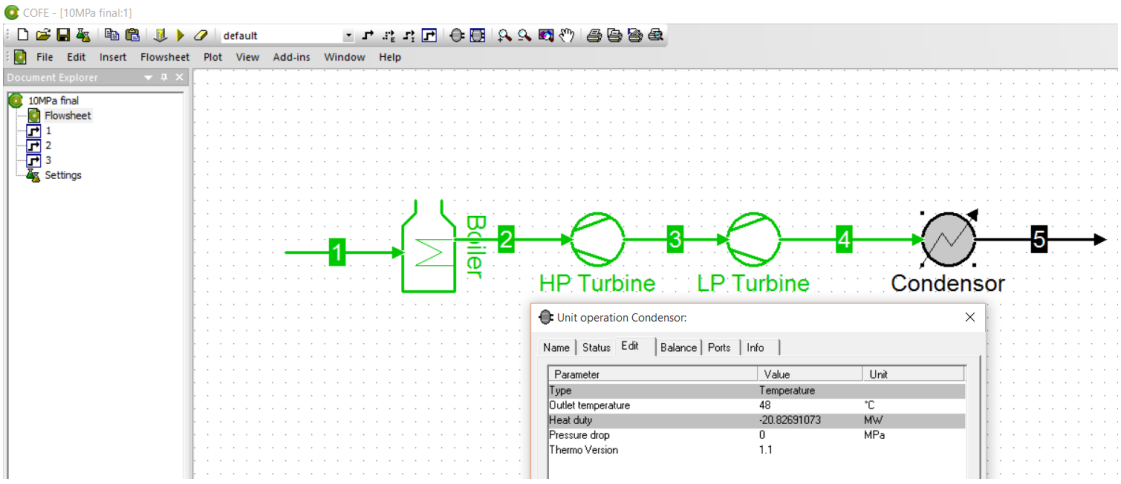


Figure 52. Insert and Specify Condenser.

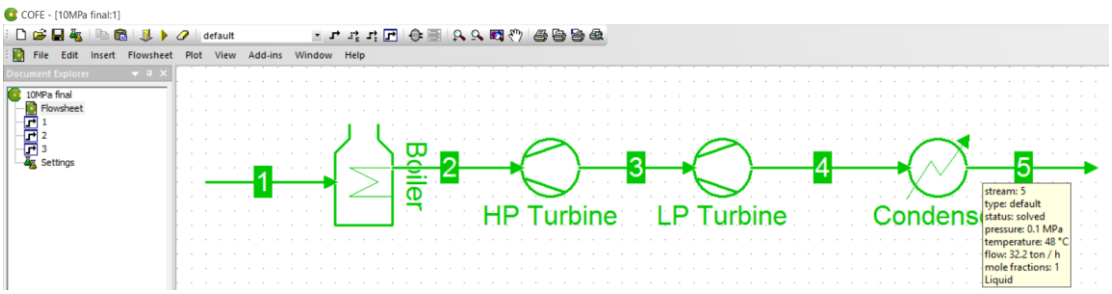


Figure 53. Solution of the system.

After the condenser, we insert the LP-Pump following the same process. The saturated liquid enters to the feed pump, where pressure rises at 10MPa with a small increase of temperature at 48.95^{o}C, to finally close the cycle and end up to the boiler.

However, in actual steam power cycle, which is quite different from the ideal Rankine cycle there are heat losses as well as losses in the amount of liquid, during the process, which is usually replaced after the condenser, in a feed water heater before entering into the boiler. Here, for our convenience, we assume an ideal cycle without any losses. Thus as we assume that there is no feed water heater, the amount of liquid exiting the condenser will insert immediately to the boiler without being mixed with additional water amount. Hence, the cycle starts from stream 6 where the water is compressed liquid at 48.95^{o}C and 10MPa, as presented in **Figure 56**.

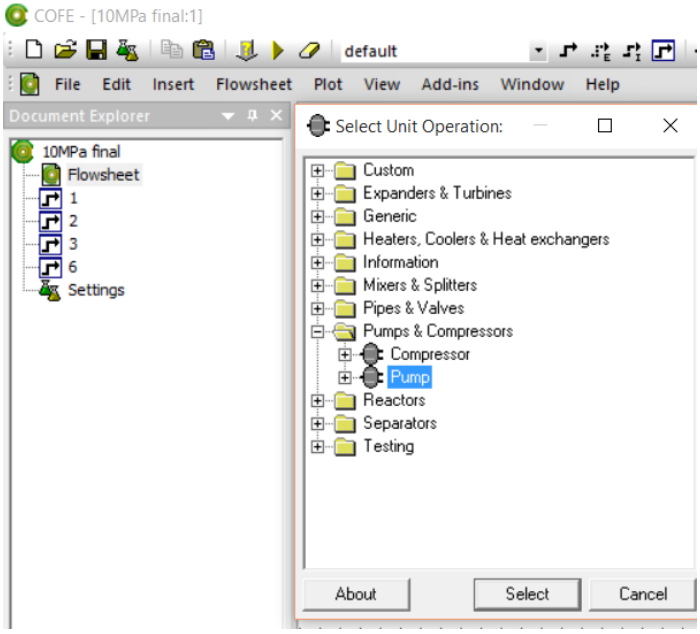


Figure 54. Insert Unit Operation LP Pump.

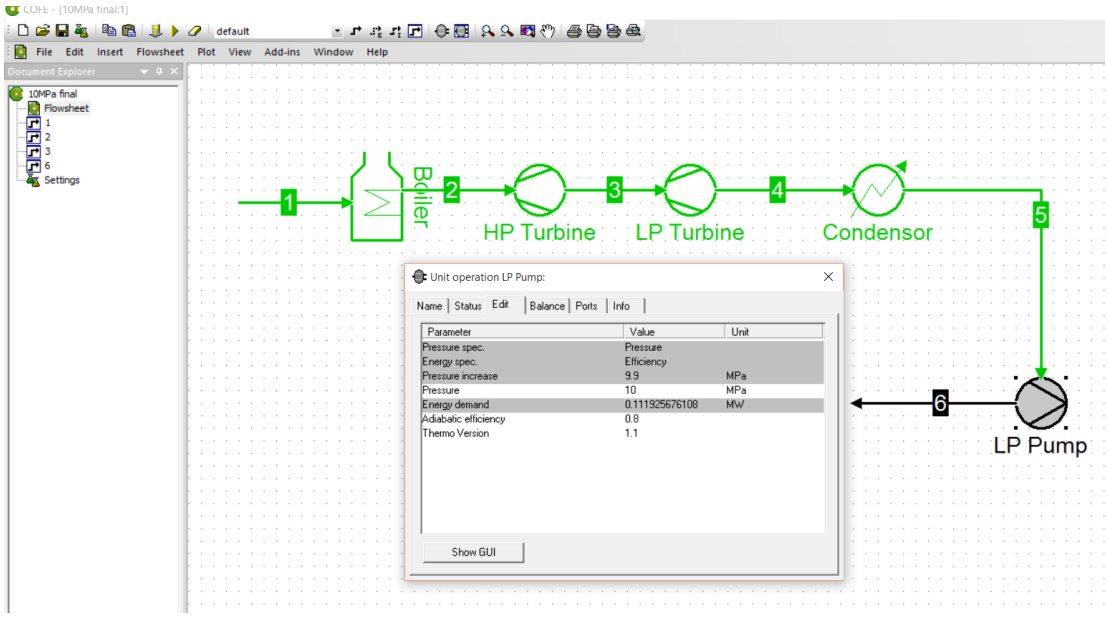


Figure 55. Solution of the specified system.

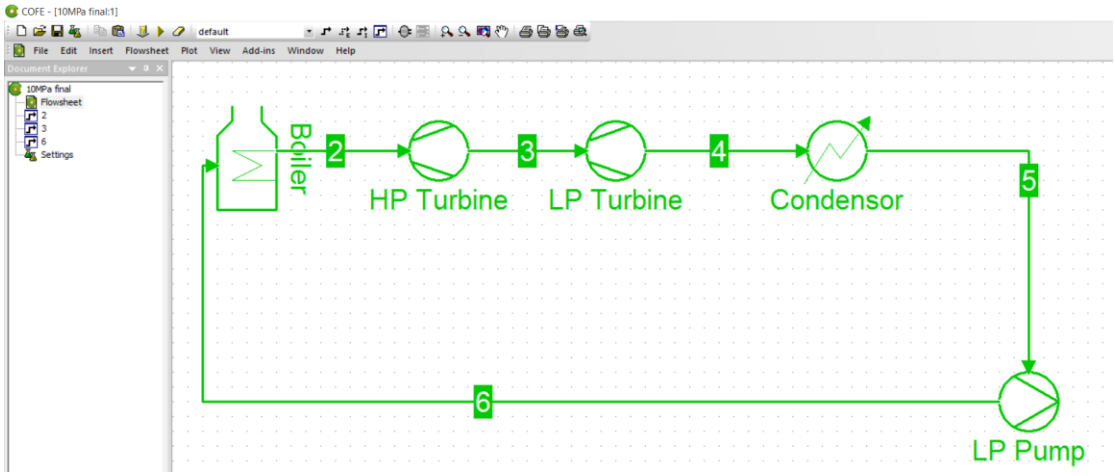


Figure 56. Simulation and Solution of the Cycle.

After the cycle design, COCO simulator offers the possibility to calculate the energy production and demand of the system. More specifically, the heat duty of boiler and condenser, the energy generation from turbines and the energy demand of the pump. Under the "Insert" menu, in **Figure 37** and selecting "Energy stream" we have the ability to calculate the work outputs and inputs for the two turbines and the pump respectively. In the same way we calculate the heat duty of the boiler ad condenser as presented in **Figure 58**. After "Solve" button the whole system turns into green and it is finally solved.

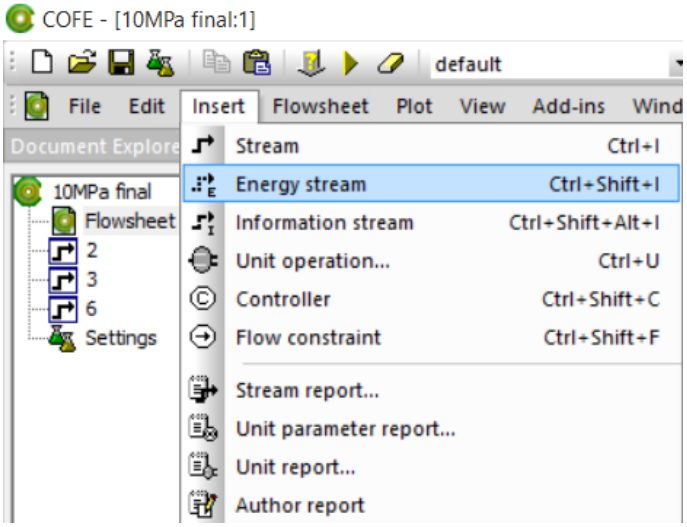


Figure 57. Insert of energy streams.

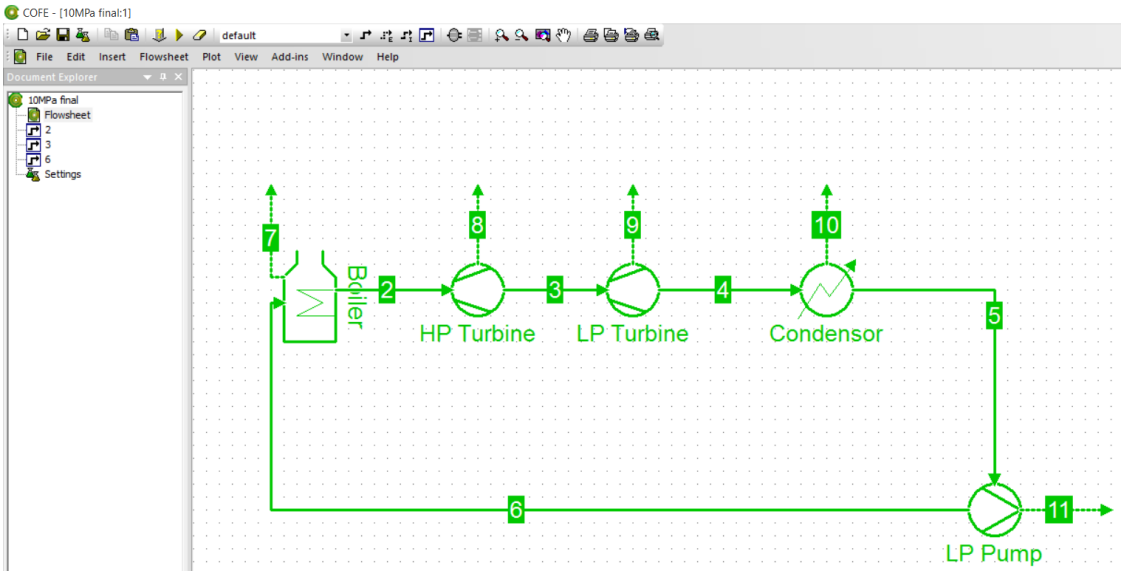


Figure 58. Solution of the Integrated System.

Now, in order to have the whole process and parameters for both streams and unit accumulated, we insert a “Stream report” and a “Unit parameter report” as shown in **Figure 59**. As a result we have two table reports showing analytically the stream and unit conditions, in **Figure 60**.

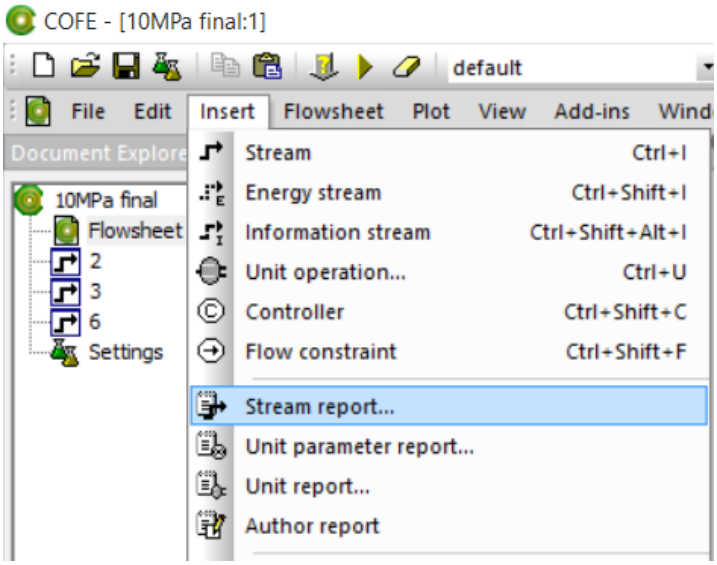
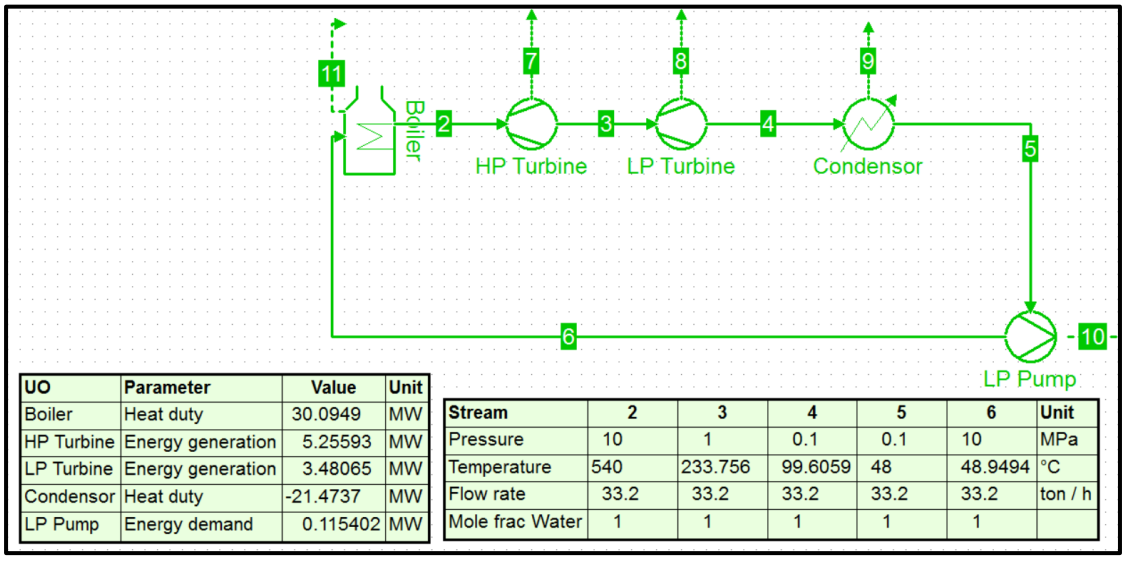


Figure 59. Insert of Stream and Unit Operation Report.



UO	Parameter	Value	Unit
Boiler	Heat duty	30.0949	MW
HP Turbine	Energy generation	5.25593	MW
LP Turbine	Energy generation	3.48065	MW
Condensor	Heat duty	-21.4737	MW
LP Pump	Energy demand	0.115402	MW

Stream	2	3	4	5	6	Unit
Pressure	10	1	0.1	0.1	10	MPa
Temperature	540	233.756	99.6059	48	48.9494	°C
Flow rate	33.2	33.2	33.2	33.2	33.2	ton / h
Mole frac Water	1	1	1	1	1	

Figure 60. Integrated Simulation of the 10MPa FBB CHP.

We follow the same steps for the other two cases, for both 2MPa and 5MPa boiler. The stream and unit operation reports from COCO simulation for these three cases are presented in **Table 17** and **Table 18**.

From the results, it is obvious that the higher the steam pressure from the boiler the higher the energy production from the high pressure turbine is. On the other hand when the steam pressure is low the low pressure turbine is more advantageous in energy production. This is the reason why in the 2MPa boiler system energy generation is almost 1.93MW while in the 10MPa boiler, 5.26MW are produced from the first turbine. Additionally a slight but not significant difference is observed in heat production between the different systems. It is understandable that the higher the temperature difference between the steam and the water in heat exchanger is, the higher the amount of heat exchange is. The cool water passes through the heat exchanger at 15^{o}C and 0.1MPa. Thus, as in the 2MPa boiler system the steam temperature is 171.75^{o}C, 23.5MW of heat exchange occur, while in the 10MPa boiler system the smallest temperature difference produces 21.47MW of heat, in order to exit from the heat exchanger at 48^{o}C.

Table 17. Stream Report.

Stream	**2**	**3**	**4**	**5**	**6**
2 MPa Fluidized Bed Boiler CHP					
Pressure (MPa)	2	1	0.1	0.1	2
Temperature (^{o}C)	540	436.36	171.75	48	48.18
Flow rate (ton/hr)	32.3	32.3	32.3	32.3	32.3
5 MPa Fluidized Bed Boiler CHP					
Pressure (MPa)	5	1	0.1	0.1	5
Temperature (^{o}C)	540	315.19	99.60	48	48.47
Flow rate (ton/hr)	32.6	32.6	32.6	32.6	32.6
10 MPa Fluidized Bed Boiler CHP					
Pressure (MPa)	10	1	0.1	0.1	10
Temperature (^{o}C)	540	233.76	99.60	48	48.95
Flow rate (ton/hr)	33.2	33.2	33.2	33.2	33.2

Table 18. Unit Operation Report.

Unit Operation	Parameter	Value (MW)		
FBB CHP Cases		2 MPa FBB	5 MPa FBB	10 MPa FBB
Boiler	Heat duty	30	30	30
HP Turbine	Energy generation	1.93	4.02	5.26
LP Turbine	Energy generation	4.69	3.88	3.48
Heat Exchanger	Heat exchange	23.5	22.23	21.47
LP Pump	Energy demand	0.021	0.056	0.115

Regarding the results from COCO simulator we have three cases of CHP plant, with different pressure steam producing fluidized boiler that can be fired with MSW of the city of Thessaloniki. About 316.6tons/day (13.2tons/h) combusted biomass at 2MPa, 5MPa and 10MPa boiler, produces 32.3ton/hr 32.63ton/hr and 33.23ton/hr of steam, respectively. Each system has a different energy output. The total electrical energy and heat production from the three systems is 6.62MW and 23.5MJ/s, 7.9MW and 22.23MJ/s and 8.74MW and 21.47MJ/s for the 2MPa, 5MPa and 10MPa FBB boiler, respectively.

In order to have a more clear aspect about the efficiency and the correctness of the systems' simulation, we compare these results with similar, already existing biomass CHP plants in the world.

Regarding, though, existing biomass CHP plants, we could consider the Vejen CHP plant, in Denmark, which is a special combined fuel system, because the steam producing boiler can be fired with either waste, straw, wood chips, or pulverized coal. The plant's annual biomass input is estimated at about 3.2tons/day, whilst the output of the system is 3.1MW and 9MJ/s heat at a steam production of 15.7tons/hr at 5MPa and 425^{o}C [124] [125].

Moreover, the Masnedø CHP plant is a biomass-fired backpressure system for electricity and district heating supply to Vordingbord, in Eastern Denmark. It consumes biomass of about 117.7ton/day, which is fired at a fluidized circulated bed boiler of 33.2MW heat duty, producing steam of 522^{o}C and 9.2MPa. The system produces electrical power of 9.5MW and 20.8MJ/s of heat output [125].

Additionally, biomass CHP plant Reuthe in Reuthe Vorarlberg in Austria, consumes about 27.3tons/day of solid biomass, producing 6.3MW of heat ad 1.3MW of electricity. Biomass is combusted in a 10MW boiler producing steam of 445^{o}C and 3.2MPa [125].

The slight differences are noted between the already existing CHP plants and those three cases, result especially from the amount and the type of biomass that is used. As, for example, the combination of waste, wood and straw has higher heating values , high energy production can be succeed with lower feedstock flow rate. In general, we could conclude that these simulation cases are acceptable and sufficient, taking into account the already existing facilities.

6.5 COCO Simulation Results

Table 19 presents an integrated and more detailed view of the three systems' characteristics and simulation results. Regarding these results we have the ability to finally select the most efficient case for the specific project.

Table 19. System Characteristic and COCO Simulation Results.

Fluidized Bed Boiler CHP in Thessaloniki			
Biomass Fuel Characteristics			
Biomass Fuel Feed (tons/day)	316		
Moisture content (%)	27.7		
Energy content (LHV as received) (MJ/kg)	8.42		
Biomass Conversion			
Boiler efficiency (zero moisture) (%)	84-95		
Boiler efficiency (moisture adjusted) (%)	80		
Heat input to boiler (MW)	30		
Plant availability factor	0.9		
Boiler Steam Conditions	**2MPa Boiler**	**5MPa Boiler**	**10MPa Boiler**
Boiler output pressure (MPa)	2	5	10
Boiler output temperature (°C)	540	540	540
Nominal steam flow (tons/hr)	32.3	32.6	33.2
CHP Back-Pressure High Pressure Turbine			
Electric output (MW)	1.93	4.02	5.26
Process steam conditions (MPa)	1	1	1
Process steam flow (tons/hr)	32.3	32.6	33.2
HP-Turbine output Temperature (°C)	436.36	315.19	233.76
HP-Turbine Efficiency (%)	90	90	90
CHP Low Pressure Turbine			
Electric output (MW)	4.69	3.88	3.48
Process steam conditions (MPa)	0.1	0.1	0.1
Process steam flow (tons/hr)	32.3	32.6	33.2
LP-Turbine output Temperature (°C)	171.75	99.60	99.60
LP-Turbine Efficiency (%)	90	90	90
Condenser-Heat Exchanger			
Thermal energy output (MW)	20.5	19.3	18.6
Liquid Water output Temperature (°C)	48	48	48
Feed Pump			
Work input (MW)	0.021	0.056	0.115
Liquid Water output Temperature (°C)	48.18	48.47	48.95
Liquid Water output Pressure (MPa)	2	5	10
Feed Pump Efficiency (%)	80	80	80
CHP			
CHP Efficiency (%)	89.65	89.8	90.2
Electrical Efficiency (%)	21.35	25.5	28.2
Thermal Efficiency (%)	75.8	71.7	62.25

The most commonly used approach to determining a CHP system's efficiency is to calculate total system efficiency. The total system efficiency (η_{CHP}) of a CHP system is the sum of the net useful power output (W_{out}) and net useful thermal outputs (Q_{out}) divided by the total fuel input (Q_{fuel}), as shown below. Alternatively, the η_{CHP} is also the sum of the electrical (η_e) and thermal (η_{th}) efficiency of the system. Considering that the software does not provide the possibility to calculate the heat losses throughout the whole process, we have to take into account 13% as typical thermal losses. Thus, the thermal output for the three cases will be 20.5MW, 19.3MW and 18.6MW.

$$(3)\ \ \eta_{CHP} = \frac{W_{out}+Q_{out}}{Q_{fuel}} \qquad (4)\ \ \eta_e = \frac{W_{out}}{Q_{fuel}} \qquad (5)\ \ \eta_{th} = \frac{Q_{out}}{Q_{fuel}}$$

The total CHP plant efficiencies calculated for each one of the three cases are 89.65%, 89.8% and 90.2% for 2MPa, 5MPa and 10MPa FBB CHP system, respectively. Although, the 10MPa FBB CHP plant seems to have higher efficiency**,** there are no significant differences concerning the total CHP efficiencies. However, important differences are noticed in thermal and electrical energy production separately. In essence, electrical (η_e) and thermal (η_{th}) efficiency for the first case is 21.35% and 68.3%, respectively. For the second case, η_e is 25.5% and η_{th} is 64.3%, while for the third case η_e is 28.2% and η_{th} is 62%. In order to select the most suitable case for the specific project we must take into account the amount and the type of energy needs of Thessaloniki's habitants.

According to the survey of energy consumption in households, conducted by the Hellenic Statistical Authority (HSA) during the period October 2011-September 2012, the average power consumption of each household, to cover the energy needs, in the country was 13,994kWh/year. 81% of this energy is consumed for a household's needs for space heating and cooking, while the overall annual energy needs for oil heating and electricity are 44.1% and 26.8% respectively. The average annual thermal and electrical energy consumption per household in Greece is 10,244KWh and 3,750KWh, respectively [127] [128].

Taking into account these energy needs, as well as the energy production of each case and the 90% operating availability of the CHP facility we conclude that for 7,884 annual operation hours:

- The 2MPa boiler CHP plant produces 52,192,000kWh/year of electricity and 179,170,000kWh/year of thermal energy, covering thermal and electrical energy needs of 17,490 and 13.000 households, respectively and 30,490 households totally.
- The 5MPa boiler CHP plant produces 62,283,000kWh/year of electricity and 168,682,000kWh/year of thermal energy, covering thermal and electrical energy needs of 16,470 and 16,600 households, respectively and 33,070 households totally.
- The 10MPa boiler CHP plant produces 68,906,000kWh/year of electricity and 162,564,000kWh/year of thermal energy, covering thermal and electrical energy needs of 15,870 and 18,380 households, respectively and 34,250 households totally.

Regarding Thessaloniki's population at 1,110,000 habitants and 5 habitants as the average number of members per household, the total number of households for Thessaloniki is around 222,000 [127]. Thus, the first case covers the total energy needs of 13.73% of the city's households, the second serves the 14.9%, while the third the 15.43%. It is obvious there are slight differences between the three cases. The first case provides higher amount of thermal energy and covers the thermal energy needs of 9.26% more than these of the third case. On the other hand, the latter covers the electrical energy needs of 29.3% more than the former, while in total energy needs it overweighs for almost 2%.

7. Conclusion

The constant increase of Municipal Solid Waste (MSW) as a result of the population increase, urbanisation as well as human development is a severe global issue threatening human health, environmental sustainability. The uncontrolled deposition of MSW in landfills without specific treatment is a serious pollution source. Already, in 2008, landfills contribution to total world methane production was 23%. In 17th of June 2008, the EU Parliaments introduces the Waste Framework Directive and considers the Waste-to-Energy (WtE) as an energy recovery operation that must be a part of every integrated waste treatment system. WtE system is an environmental solution for the waste management issue as well as an alternative renewable energy source. Currently, 520 WtE plants are operating, in Europe, with about 95 million tons of MSW and commercial waste to be treated annually. Over the last five years, the capacity of European WtE grew by 24% annually. WtE facilities exploit the energy content of MSW to produce electricity, steam, heating and fuels while both reducing waste's volume by 90% and CO_2 emission by around 50%. However, energy recovery from waste facilities are not yet applied in Greece, with 293 Uncontrolled Waste Disposal Sites still operating and facing faces serious penalties from EU for not conforming to Directives. The lack of an integrated waste treatment with energy recovery in Greece results in landfilling of 91% of the total amount of MSW, while only 8% is recycled.

The majority of WtE plants in the world operate with waste combustion. Biomass combustion is the most advanced, common and simplest technology to extract both heat and electricity. Biomass CHP facilities can include a high variety of biomass fuels such as wood, agricultural residues, wood pulping liquor and MSW. Beyond all the already existed combustion technologies, Fluidized Bed Boiler is the most suitable for MSW combustion because of its capability of handling high ash and moisture content and extremely low heating values fuels. The fluidized bed boiler operates at temperature between 800°C and 950°C, while reaching high capacity ranging between 20MW and 100MW with limited emissions.

The objective of the specific thesis work was to study the modelling of a Fluidized Bed Boiler CHP facility for energy production from MSW of Thessaloniki, Greece,

by using the COCO simulation software. The total solid biodegradable fraction of city's MSW is about 104,000tons/year corresponding to 316.6tons/day incinerated and producing 166,100tons of CO_2 annually. For this amount of feedstock, three different pressure types of fluidized boilers, of 30MW capacity each, have been examined. The boilers pressures that have been studied are 2MPa, 5MPa and 10MPa. The CHP plant also consists of a high and a low pressure turbine, a condenser and a low pressure pump. According to available experimental data the efficient of the boiler and feed pump was determined at 80%, both turbines at 90%, whilst heat loses of the system were considered to be at 13%.

The COCO results indicate that 316.6tons/day of the city's MSW is combusted at 2MPa, 5MPa and 10MPa boiler produces 32.3ton/hr 32.63ton/hr and 33.23ton/hr of steam, respectively. Each system has a different energy output. The total CHP plant efficiencies calculated for each one of the three cases are 89.65%, 89.8% and 90.2% for 2MPa, 5MPa and 10MPa FBB CHP system, respectively. The total electrical energy and heat production from the three systems is 6.62MW and 20.5MJ/s, 7.9MW and 19.3MJ/s and 8.74MW and 18.6MJ/s for each case, respectively. Regarding the population of Thessaloniki, the first case covers the total energy needs of 13.73% of the city's households, the second serves the 14.9%, while the third the 15.43%.

As it is obvious, there are no major differences between the results of each case. However there is a dilemma concerning the selection of the most appropriate case for the specific occasion. The final choice lays on what we want to produce and which society's needs we want to cover. In essence, in case we want to cover the electricity needs more than the thermal then the 10MPa FBB CHP plant would be more suitable. On the other hand, if we concern more about the thermal needs we should choose the 2MPa FBB CHP plant. The fact is that Thessaloniki thermal needs outweigh the electricity demand. From this point of view the first case scenario would be suitable. Nevertheless, the third case provides a higher total energy production while it does not fall short in heat production as well.

Due to the fact that this thesis does not include an economic analysis for these cases, we are not in position to come to a decision as we do not know the profitability of each project. In terms of efficiency and total energy production the third case seems to be ideal. However, the results might be different when the economic analysis occurs.

Conclusively, future work of this thesis work could be the economic analysis of each case and the final selection of the most profitable case. Besides this, another future action should be realized is the spatial planning of the CHP facility in an appropriate area. Additionally, the determination of the emissions not only from the CHP operation but also from the total transportation system should be included, as well as the calculation of the waste disposal reduction. Finally, a total feasibility study for the project's viability and efficiency should be take place. While another future work could be the study and modelling of a biomass CHP unit for the MSW exploitation of the greater area of Thessaloniki, including MSW of the other Municipalities.

Bibliography

[1] Kyosti V. Sarkanen, David A. Tillman, 1979. Progress in Biomass Conversion.

[2] *John Willey & Sons, Chichester Hagan, 1996. Biomass conversion and technology. p. 8.*

[3] *D.L. Klass, 1989. Biomass for renewable energy fuels and chemical.*

[4] *D. Vamvouka, 2009. Biomass, Bioenergy & Environment.*

[5] *Papagrigorakis, Manolis J. Yapijakis, Christos Synodinos, Philippos N. Baziotopoulou-Valavani Effie, 2006. DNA examination of ancient dental pulp incriminates typhoid fever as a probable cause of the Plague of Athens.* International Journal of Infectious.

[6] *1665.* The Great Plague of London, Contagion, Historical Views of Diseases and Epidemics. *Harvard University.*

[7] *Mumford, L., 1961.* The City in History. New York: Harcourt, Brace & World Solid Waste Engineering. *Second Edition, SI.*

[8] *William A. Worrell and P. Aarne Vesilind, 2012.* Solid Waste Engineering. *Second Edition. Bucknell University.*

[9] *George Tchobanoglous, Frank Kreith, 2002.* Handbook of Solid Waste Management. *Second Edition.*

[10] *Human Development Report, 2010.* The Real Wealth of Nations: Pathways to Human Development.

[11] *A. Imad, 2012.* Municipal Solid Waste Management in Developing Countries: Future Challenges and Possible Opportunities, *Khatib, Palestine Polytechnic University, Hebron, Palestine.*

[12] *E.A.Voudrias, Democritus University of Thrace, 2004.* university notes in the course of Municipal Solid Waste Technologies and Managemen.

[13] *Mouri, G., Takizawa, S., Oki, T., 2011. Spatial and temporal variation in nutrient parameters in stream water in a rural-urban catchment, Shikoku, Japan: Effects of land cover and human impact, J. Environmental Management. pp. 92, 1837–1848.*

[14] *Bellos, D., Sawidis, T., Tsekos, I., 2004. Nutrient chemistry of River Pinios (Thessalia, Greece).* Environment International, *pp. 30, 105–115.*.

[15] *A. Bagchi, 1989.* Design, construction, and monitoring of sanitary landfills. *New York: John Wiley.*

[16] *Ehrig. H.J., 1988.* Water and Element Balances of Landfills, in Lecture Notes in Earth Sciences, The Landfill, *Berlin: P. Baccini (Editor), Springer-Verlag Press.*

[17] *Halvadakis CP., 1983.* Methanogenesis in solid-waste landfill bioreactors, PhD Dissertation, *Stanford University, Stanford CA.*

[18] *Harris JM. Gaspar JA., 1989. Management of leachate from sanitary landfille, Environmental Engineering Conference Proceedings. Malina JF. (Editor).* New York: ASCE, *p. 320–333.*

[19] *M. El-Fadel, E. Bou-Zeid, W. Chahine, B. Alayli, 2002. Temporal variation of leachate quality from pre-sorted and baled municipal solid waste with high organic and moisture content. June, p. 269–282.*

[20] *Meena Khwairakpam, Renu Bhargava, 2008. Vermitechnology for sewage sludge recycling. April, p. 949.*

[21] *Hefa Cheng, Yuanan Hub, 2010. Municipal solid waste (MSW) as a renewable source of energy: Current and future practices in China. January.*

[22] *CEWEP (Confederation of European Waste-to-Energy Plants), 2013.* Country Reports on Waste Management: 1600 Waste to Energy facilities in the World.

[23] *Energy Council , 2013.* World Energy Resources: Waste to Energy.

[24] *TECHNOLOGY DATA FOR ENERGY PLANTS, 2012.* Generation of Electricity and District Heating, Energy Storage and Energy Carrier Generation and Conversion. *[Online] Available at: https://www.energinet.dk*

[25] *Themelis, Nickolas J. and Zhixiao Zhang, 2010. The importance of WTE to China and the global climate.* Proceedings Waste Engineering, *May.*

[26] *L. Qiu, N.J. Themelis, 2012. Analysis of the economics of Waste-to-Energy plants in China Earth Engineering Center, Columbia University.*

[27] *Dr. Efstratios Kalogirou, PresidentN. J. Themelis, Director, 2012.* Waste-to-Energy Research and Technology Council, *USA: SYNERGIA, Earth Engineering Center, Columbia University.*

[28] *Manolis Klados, 2012.* WASTE TO ENERGY TECHNOLOGY. *[Online] Available at: http://www.imbaenergyclub.gr [Accessed 11 August 2015].*

[29] *A. Gerasimou, President of the Greek Association Development of Biomass, 2013. Rural Biomass and Potential Exploitation in Greece. October.*

[30] *M. Hristou, Biomass Department of RES Center, CRES, 2010. Potential of Biomass in Greece.*

[31] *Esayas Alemayehu, Jimma University, 2004. Solid and Liquid Waste Management.*

[32] *EIONET European Topic Centre,* Sustainable Consumption and Production. *[Online]*
Available at: http://scp.eionet.europa.eu

[33] *Ministry for the Environment, Energy and Climate Change, 2011, [Online] Available at: http://www.ypeka.gr*

[34] *Ministry for the Environment, Energy and Climate Change, 2012, [Online] Available at: http://www.ypeka.gr*

[35] *European Environmental Agency (EEA), 2013.* Managing municipal solid waste-a review of achievements in 32 European countries.

[36] *Alexandros Aivazidis, Democritus University of Thrace, 2007.* university notes in the course of Wastewaters and Wastewater Technologies and Management.

[37] *Egyptian Environmental Affairs Agency (EEAA), 2002.* Industrial Wastewater Treatment Plants Inspection Manual.

[38] 2012 WFD review by the European Commission. *[Online] Available at: http://eur-lex.europa.eu/legal*

[39] Directive [2008/98/EC] of the European Parliament and of the Council on waste.

[40] *E.A.Voudrias, Democritus University of Thrace, 2005.* university notes in the course of Municipal Solid Waste Technologies and Management.

[41] *Heracleous E., International Hellenic University (IHU), 2014.* university notes in the course HydroPower-Wave and Tidal Energy-Bioenergy.

[42] *Peter McKendry, 2002. Energy production from biomass (part 2): conversion technologies.*

[43] *FAO: Corporate Document Repository, Natural Resources Management and Environment Department, n.d.* Waste Treatment and use in agriculture. *[Online] Available at: http://www.fao.org/ [Accessed 18 August 2015]*.

[44] *Konstantinos P. Tsagarakis , Dr Nigel J. Horan, Prof. Duncan D. Mara, Dr Andreas N. Angelakis, 2002. Management of Biosolids from Municipal Wastewater Treatment Plants in Greece.*

[45] *Eurostat, 2015.* Municipal waste statistics. *[Online] Available at: http://ec.europa.eu*
[Accessed 14 August 2015].

[46] *B.N. Karagianis, Chemical Engineer, National TechnicalL University of Athens (NTUA), 2013.* Solid Waste Treatment-Recycling. *[Online] Available at: http://thess.pde.sch.gr [Accessed 13 December 2015]*.

[47] *G. Tchobanoglousetal, George Tchobanoglous, Hilary Theisen, S. A. Vigil, 1993.* Integrated solid waste management. *McGraw-Hill (Editor).*

[48] *Dimitrios C. Panagiotakopoulos, 2002. Sustainable Management of Municipal Solid Waste.*

[49] *K. Songtao, W Kun, E. Kalogirou, N.J.Themelis, A.C.Bourtsalas. Waste management in Greece and in China and potential for waste-to-energy.*

[50] *Dr. Efstratios Kalogirou, n.d.* WASTE TO ENERGY SOLUTION FOR GREEK MSW. *[Online] Available at: http://www.wtert.gr [Accessed 11 December 2015]*.

[51] *Technical Chamber of Greece , 2006.* Municipal Solid Waste Treatment the Case of Attica.

[52] *Ioannis Bakas and Leonidas Milios, Copenhagen Resource Institute, European Environment Agency (EEA), 2013.* Municipal waste management in Greece.

[53] *Dr. Efstratios Kalogirou, President N. J. Themelis, SYNERGIA, Earth Engineering Center, Columbia University, USA, n.d.* Waste-to-Energy Research and Technology Council. *[Online] Available at: http://www.wtert.gr [Accessed 11 December 2015]*.

[54] *Technical Chamber of Greece, 2006.* Municipal Waste Treatment and Urban Environment. *[Online] Available at: http://web.tee.gr/*

[55] *Eurostat, n.d.* Environment in the EU Each person in the EU generated 481 kg of municipal waste in 2013. *[Online] Available at: http://www.avgi.gr/ [Accessed 10 August 2015]*.

[56] *Eurostat, 2015.* In SL the 81% of the municipal waste in Greece. *[Online] Available at: http://www.avgi.gr/ [Accessed 10 August 2015]*.

[57] *Ministry for the Environment, Energy and Climate Change, 2007.* Annex II: Review and Evaluation of Needs in Solid Waste Treatment Projects. *[Online] Available at: www.dikaiologitika.gr [Accessed 10 August 2015]*.

[58] *Ministry for the Environment, Energy and Climate Change, 2014.* Fine 54,450 euro per day for 239 Sanitary Landfills. *[Online] Available at: www.dikaiologitika.gr [Accessed 8 August 2015]*.

[59] *Ministry for the Environment, Energy and Climate Change, 2015.* In 15 days the fine for illegal Sanitary Landfills. *[Online] Available at: www.dikaiologitika.gr [Accessed 10 August 2015]*.

[60] *Ministry of Interior and Administrative Reconstruction, 2010. [Online] Available at: http://www.ypes.gr/el/ [Accessed 10 August 2015]*.

[61] *CEWEP (Confederation of European Waste-to-Energy Plants) , n.d.* Available at (last access 11/8/2015). *[Online] Available at: http://www.cewep.eu/ [Accessed 11 August 2015]*.

[62] *Tsagarakis, K.P., 1999.* The Treatment of Municipal Wastewater in Greece, *Ph.D. Thesis, Leeds, United Kingdom: University of Leeds, School of Civil Engineering.*

[63] *Tsagarakis, K.P., P. Tsoumanis, K. Chartzoulakis and A.N. Angelakis, 2001.* Water Resources Status Including Wastewater Treatment and Reuse in Greece Related Problems and Prospectives. *Second Edition. International Water Resources Association (IWRA).*

[64] Tsagarakis, K.P., G.E. Dialynas and A.N. Angelakis. 2004. Water Resources Management in Crete (Greece) Including Water Recycling and Reuse and Proposed Quality Criteria. Agricultural Water Management,

[65] *A.Karamanos, S. Aggelides, P. Londra, 2007. Non-Conventional Water Use in Greece.*

[66] *European Commission - Press release database, 2015.* Commission takes Greece to Court over poor waste water treatment presenting a risk to public health Brussels. *[Online] Available at: http://europa.eu*

[67] EU takes action over wastewater treatment in Greece. *[Online] Available at: http://www.globalprocessingmag.com/ [Accessed 16 August 2015]*.

[68] *Mark Döing, 2014.* Time Out: For Waste to Energy in Europe. *[Online] Available at: www.waste-management-world.com [Accessed 11 August 2015]*.

[69] *Manolis Klados, 2012.* WASTE TO ENERGY TECHNOLOGY. *[Online] Available at: http://www.imbaenergyclub.gr [Accessed 11 August 2015]*.

[70] *European bioplastic, 2015.* Energy Recovery.*[Online] Availableat:http://en.european-bioplastics.org/*

[71] *CEWEP (Confederation of European Waste-to-Energy Plants), 2014.* Country Reports on Waste Management.

[72] *Jan Manders,Deputy President CEWEP, 2013.* Integrated waste management of MSW across Europe Waste to Energy as a professional route to treat residual waste.

[73] *Donald Klass, n.d.* An Introduction to Biomass Energy a Renewable Resource. *[Online]*
Available at: www.bera1.org, [Accessed 18 August 2015].

[74] *Nisha Sriram, 2005. Renewable Biomass Energy.*

[75] *Peter McKendry, 2001. Energy production from biomass (part 1): overview of biomass.*

[76] *Ralph E.H. Sims (New Zealand), Robert N. Schock (USA), 2007. Energy Supply.*

[77] *Sameer Maithel, 2009.* Biomass Energy-Resource Assessment Handbook.

[78] Biofuels. *[Online] Available at: http://www.agroenergy.gr [Accessed 18 August 2015]*.

[79] *INVENT – Integrated Waste Management modules for different courses of graduate studies,* Biomass combustion processes. *[Online] Available at: http://www.invent.hs-bremen.de*
[Accessed 13 October 2015].

[80] West to Energy Conversion routes. *[Online] Available at: http://www.bioenergyconsult.com*
[Accessed 22 August 2015].

[81] Biomass Power. *[Online] Available at: http://www.yokogawa.com [Accessed 22 August 2015]*.

[82] *EPTA, 2010.* Study for construction a MSW treatment facility, Analysisi and Examination of available technologies of MSW processing for the region of Epirus.

[83] *Austrian Ministry of Life, 2010.* Waste–to–Energy in Austria, White Book.

[84] *Environmental Protection Agency (EPA) Combined Heat and Power Partnership, 2007.* Biomass CHP Catalog, Power Generation Technologies.

[85] *IEA Bioenergy,* Biomass Combustion and Co-firing: an Overview. *[Online] Available at: http://www.ieabioenergy.com*

[86] *V. Belgiorno, G. De Feo, C. Della Rocca, Napoli Department of Civil Engineering, University of Salerno, 2002. Energy from gasification of solid wastes. 11 September.*

[87] *J.A. Ruiz, M.C.Juarez, M.P.Morales, P.Munoz, M.A.Mendıvil, 2013. Biomass gasification for electricity generation: Review of current technology barriers.*

[88] *Soulios V., Kosmas D., Metavisiadis V., Marnelos G., 2015. Productiona of Electricity from Municipal Solid Waste in Kos.*

[89] *A.V. Bridgwater, D. Meier, D. Radlein, 1999. An overview of fast pyrolysis of biomass.*

[90] *Peter McKendry, 2002. Energy production from biomass (part 3): gasification technologies.*

[91] *U.S. Department of Energy, Bioenergy Technologies Office, n.d.* Energy Efficiency and Renweable Energy. *[Online] Available at: http://www.energy.gov [Accessed 25 August 2015].*

[92] *M.M Kucuk, A. Demirba, n.d. Biomass Conversion Processes.* 1997.

[93] *Lise Appelsa, Joost Lauwersa, Jan Degrhvea, Lieve Helsenb, Bart Lievensc, Kris Willemsc, Jan Van Impea, Raf Dewila, 2011. Anaerobic digestion in global bio-energy production: Potential and research challenges.*

[94] *Smet E, Van Langenhove H, De Bo I. , 1999. The emission of volatile compounds during the aerobic and the combined anaerobic/aerobic composting of bio-waste.* Atmos Environment.

[95] *Appels L, Baeyens J, Degrθve J, Dewil R., 2008. Principles and potential of the anaerobic digestion of waste-activated sludge.* Prog Energy Combust.

[96] *Owens JM, Chynoweth DP, 1993. Biochemical methane potential of municipal solid waste (MSW) component.* Water Sci Technol.

[97] *Dr. Jasper van Baten, AmsterCHEM, n.d.* AN INTRODUCTION TO COCO. *[Online] Available at: http://www.cocosimulator.org*

[98] *Jasper van Baten, AmsterCHEM Michel Pons, CO-LaN, n.d.* RAPID PROTOTYPING OF UNIT OPERATION MODELS USING GENERIC TOOLS AND CAPE-OPEN. *[Online] Available at: http://www.cocosimulator.org*

[99] *Ross Taylor, Harry Kooijman, Brett Walker, 2011. Modelling Luyben's Chemical Processes with COCO and ChemSep.*

[100] *Ross Taylor, Clarkson University, Jasper van Baten, AmsterCHEM, 2010. Flowsheeting with COCO and ChemSep.*

[101] Handbook Chapter 3: CAPE-OPEN Flowsheet Simulations with ChemSep. *[Online]*
Available at: http://www.chemsep.com [Accessed 10 September 2015].

[102] GCO-Final Technical report: Global CAPE-OPEN Delivering the power of component software and open standard interfaces in computer-aided process engineering. *[Online] Available at: http://www.ims.org [Accessed 10 September 2015]*.

[103] ChemSep Modelling Separation Process. *[Online] Available at: http://www.chemsep.org [Accessed 10 September 2015]*.

[104] *Jasper van Baten AmsterCHEM, Delft, The Netherlands, Harry Kooijman and Ross Taylor Clarkson University. Why COCO or Do we really need another Flowsheeting progam, even if it is free?.*

[105] *Richard Baur, Anja Olijve, Peter Nellen, Jasper van BatenGeneral.* Introduction on CAPE OPEN Demo of the amine absorption model Demo of the hydrotreating model Demo of model prototyping toolboxes in Excel & MatLab CAPE-OPEN applications in Shell.

[106] *Jasper van Baten, Ross Taylor, Harry Kooijman.* Using Chemsep, COCO and other modeling tools for versatility in custom process modeling.

[107] *Dr. Jasper van Baten.* FLOWSHEET MONITORING: HOW, WHAT AND WHY?.

[108] *Maurizio Fermeglia, Gennaro Longo, Letitia Toma, 2008.* COWAR: A CAPE OPEN Software Module for the Evaluation of Process Sustainability.

[109] *William M. Barrett Jr., Jasper van Batenb, Todd Martin, 2011.* Implementation of the waste reduction (WAR) algorithm utilizing flowsheet monitoring.

[110] *Manuel Rodríguez, Adrián Sáiz, 2013.* Industrial Methanol from Syngas: Kinetic Study and Process Simulation.

[111] [126] John Vos, (2005), "Biomass Energy for Heating and Hot Water Supply in Belarus Best Practice Guidelines Part A: Biomass Combustion"

[112] [127] UNEP Technical Study Report on "Biomass Fired Fluidized Bed Combustion Boiler Technology for Cogeneration" http://www.unep.org

[113] European Biomass Industry Association http://www.eubia.org/index.php/about-biomass/combustion/medium-to-large-scale-combusters

[114] [129] Qunxing Huang, Yong Chi, Nickolas J. Themelis, (2013) A Rapidly Emerging WTE Technology: Circulating Fluid Bed Combustion

[115] U.S. Environmental Protection Agency (EPA), 2015. *Catalog of CHP Technologies*.

[116] E. Papachristou, H. Hadjianghelou, E. Darakas, K. Alivanis, A. Belou, D. Ioannidou, E. Paraskevopoulou, K. Poulios, A. Koukourikou, N. Kosmidou, K. Sortikos, 2009. Perspectives for integrated municipal solid waste management in Thessaloniki, Greece.

[117] Feleskoura Christina, Papaioannou Eleni, 2004. Dissertation: Modern Technologies of waste recycling, treatment and energy management of wastes.

[118] *I.S. Antonopoulos, A. Karagiannidis, E. Kalogirou, 2010. Estimation of Municipal Solid Waste Heating Values in Greece in the Frame of Formulating Appropriate Scenarios on Waste Treatment.*

[119] *Nikolaos Mourouzidis, 2015. The challenge of waste management in Thessaloniki.*

[120] *Christopher J. Koroneos, Evanthia A. Nanaki, 2012. Integrated solid waste management and energy production - a life cycle assessment approach: the case study of the city of Thessaloniki.*

[121] *C. Feleskoura, E. Papaioannou, 2004. Modern MSW recycling Technologies, Managemend and Energy Treatment of MSW.*

[122] *D.L. Granatstein. Technoeconomic Assessment of Fluidized Bed Combustors as Municipal Solid Waste Incinerators: A Summary of Six Case Studies.*

[123] Fluidized Bed Technology - Overview. *[Online] Available at: http://energy.gov/fe/science [Accessed 22 November 2015]*.

[124] 2014. *The Benefits of Supercritical Boilers.* [Online] Available at: http://www.nationalboiler.com/ [Accessed 22 November 2015].

[125] CRES, 2001. Denmark: Current situation on CHP and biomass CHP in the national energy sector.

[126] *Biomass CHP Plant Reuthe, Reuthe Vorarlberg, Austria.* [Online] Available at: www.vol.at/vkw

[127] Regulation Energy Performance of Buildings - Ministry of Environment and Energy , n.d. *Energy consumption in greek households.* [Online] Available at: http://www.kenaktools.gr

[128] Municipal Enterprise of Sykies, 2007. *Integrated Local Sustainable Development Programme municipality of Sykies,* Thessaloniki.